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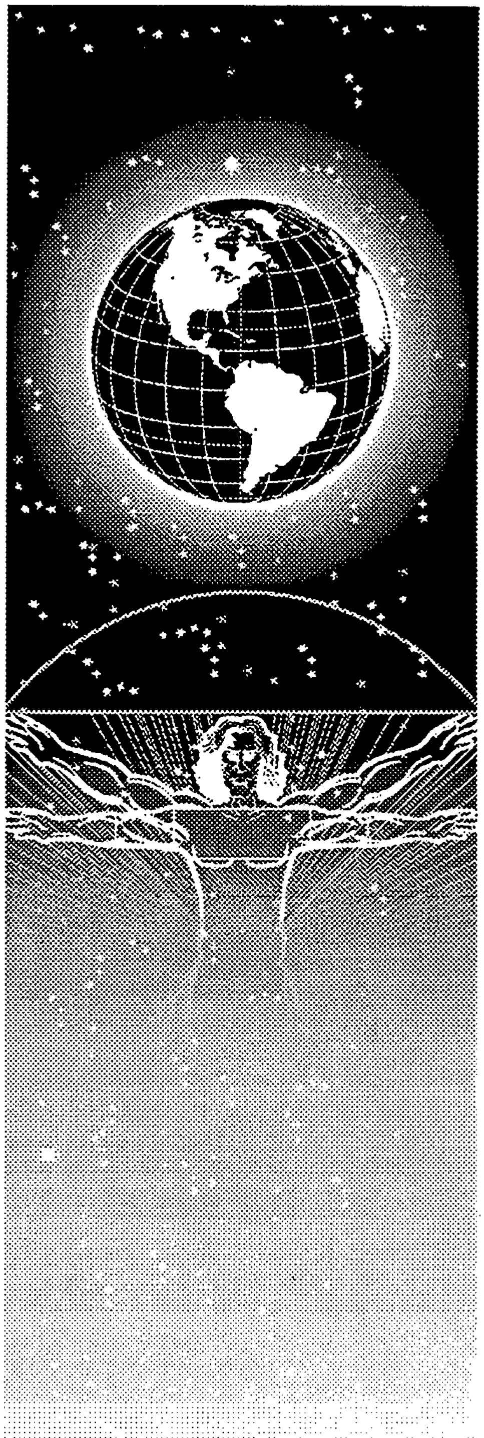

UNITED STATES AIR FORCE
ARMSTRONG LABORATORY

MULTIFACTOR DETERMINANTS OF VISUAL ACCOMMODATION AS A CRITICAL INTERVENING VARIABLE IN THE PERCEPTION OF SIZE AND DISTANCE: PHASE I REPORT

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13. ABSTRACT *(Maximum 200 words)*

The accuracy of visual perception, specifically, the accuracy of size and distance judgment, affects human performance at the boundary of today's display technology envelope. A variety of long-standing and state-of-the-art contact and contact analog display and media technologies (including virtual reality and environmental displays) are being specified and engineered without the benefit of critical and fundamental information that is now accessible. This technical report takes a conceptual, meta-analytical approach to evaluating a multidisciplinary literature regarding this domain. The findings converge, across a wide variety of clinical, experimental, and psychophysiological research, on an integrative conceptual framework. They support the value of researching a hypothesized set of relationships between the human visual synkinetic triad and the perception of size and distance. Specifically, measurable visual accommodative subsystem states and specifiable processes are implicated as critical intervening mechanisms. These mechanisms have the potential to provide avenues for prediction and practical intervention. This technical report is a stand-alone tutorial and is the final product of the background research phase for WU 1123-C3-94. At submission, instrumentation for the experimental phase of this workunit is nearing completion.

14. SUBJECT TERMS

dark focus; distance perception; head-up virtual images; HUD; moon illusion; T-O-P Model; retinal stretch; Size-Distance Invariance Hypothesis; size perception; tonic focus; Tri-Centroid; virtual reality; visual perception; visual accommodation; zoom-lens hypothesis

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PREFACE

This report is the product of the initial phase of a research project in the domain of visual perception, W.U. 1123-C3-94. The work was undertaken as a multidisciplinary effort to identify and explore visual human factors likely to affect engineering principles at the boundary of the current display design envelope. As a basic and exploratory research project, it is intended to develop enabling technologies for operational, training, and laboratory applications. This technical paper and the experimentation it precedes will provide a basis and opportunity for inter-divisional cooperative research and proposal-generation, initially, in the Virtual Reality display technology area. Special thanks are extended to Major Eric Duncan for determined source document retrieval efforts, impeccable project management support and, particularly, for invaluable hours of critical listening during the evolution of this product. Dr. Stanley Roscoe and Mr. Louis Corl of Illiana Aviation Sciences, Ltd., have invested patient consultation, insight, and expertise well beyond contract requirements. I am grateful to each of them for making this effort both possible and important.

INTRODUCTION

Context and Focus

This is a background research document initiating a basic and exploratory investigation within the domain of human visual perception. The scope of this background is much broader than the specific stream of research it introduces. This added breadth is intentional. It is specifically geared to offer psychologists and instructional technologists an opportunity to review in depth, update, and, possibly, expand their awareness of factors implicated in visual perception that might affect performance subsequent to training and instructional interventions. The specific psychological phenomena of interest are human abilities to judge accurately, or systematically misjudge, the sizes of and distances to objects in relatively distant real or virtual space. The underlying hypothesis is that the visual accommodative subsystem plays a decisive role in how accurately or, at a minimum, how consistently humans make such judgments. The visual accommodative system plays its role under common and definable real-world conditions, experimentally treated as selected, graded, independent variables.

Among the foreseeable implications of this hypothesis are means to improve the accuracy of size and distance judgments to benefit human system performance, training transfer, and critical safety characteristics at the "edge of the visual display technology envelope." Within the domain of human visual systems research, this effort addresses a limited set of methodological issues bridging operational and laboratory settings. Engineering parameters across a variety of applications should emerge as valuable products. These parameters would specify and guide the adjustment of selected factors in the design of both contact and contact-analog (to include virtual reality or synthetic environmental) displays. Such displays support operational command, vehicular control, training, and related operations.

The human visual system has been the subject of serious philosophical and scientific scrutiny throughout recorded history. As a direct consequence, information relevant to this research effort has been found within a variety of scientific and clinical disciplines. Helmholtz (1867/1962, Vol. III, p. 1), in his inspired treatise on physiological optics, declared:

> The sensations aroused by light in the nervous mechanism of vision enable us to form conceptions as to the existence, form and position of external objects. These **ideas** are called *visual perceptions*. ...[E]ven here there is a wide field of investigation in both physics and physiology, inasmuch as we have to determine, scientifically as far as

possible, what special properties of the physical stimulus and of the physiological stimulation are responsible for the formation of this or that particular idea as to the nature of the external objects perceived.

Physical and physiological optics, ecology, clinical and instrumental ophthalmological sciences, and traditional philosophical and psychological research contribute a foundation of data and theoretical considerations. This background research maintains an eclectic appreciation of these diverse bodies of disciplined effort. As a general strategy, discussions will converge, in a tutorial form, from boundary conditions in physical and biophysiological engineering through theoretical speculations and supporting data toward the detailed objects of the much more limited planned experimentation.

Even a superficial review of relevant literature makes it clear that the mechanisms being addressed are complex, involving multiple factors. The number of psychological studies available that explore the linkages among more than a few of these factors is understandably small. A critical aim of this research, therefore, is to expand our knowledge of such multifactor relationships while addressing, to the maximum extent possible, operational, real-world conditions and concerns.

Resolving the Domain

As previously stated, the domain of this study is the psychological phenomena of vision-based size and distance judgments; more specifically, how these judgments are mediated by the accommodative mechanisms of the human eye under selected experimental conditions.

The *visual array* (also *optical* array for purposes of this study) is limited to the static case of Hering's (1942, p. 9) *stationary binocular visual field*, "...a visual surface, as seen with the eyes stationary and in front of which nothing else is visible and which bounds the visual space." As pointed out by Gilinsky (1951), visual space and physical space are not identical, nor necessarily proportional to one another in three dimensions. Rather, visual space is a distorted transformation of physical space.

The arrangement and content of the visual array may vary across a spectrum of dimensions. These include: intensities, relative and actual orientations, positions of "objects" and "surfaces" in the array (static, dynamic, and relative), complexity, and very specific characteristics of the centrally subtended subfield. These, in turn, should change visual accommodative-demand and interact with the effects of selected real-world scene conditions.

This background research examines the relative importance of physiological, psychophysical, and psychological **individual differences**, the effects of **aperture** or **media systems** that modify or adjust content, and the **focal demand of specific object(s)** attended in the context of the visual array. Limitations and differences among individual human visual systems include physio-optical, affective, and cognitive parameters. Aperture and media interventions are frequently present in real world contact and imaging display settings. They include actual optical instruments, protective visors, filters, superimposed imaging displays, night-vision goggles, and perimeters that modify field of view. Focal demand is here defined as the quality or level of optical stimulation that is, in turn, a function of the physical and psychological characteristics of attended objects and their surroundings.

This research will ultimately increase the generalizability of prior work and will explore the relative impacts of filter-induced changes in retinal illumination under daylight viewing conditions on visual accommodation. This is relevant because the Air Force has recently begun exploratory use of a relatively low optical density "shooter's" visor versus the higher density standard visor in tactical aircraft. While investigations have demonstrated the expected benefits in enhanced acquisition of distant, relatively low contrast "bogeys," the effects of these alternatives on size and distance judgments have not been explored. Objects of investigation, therefore, will include the impact of these relatively moderate but different optical densities and the even denser filtration, not only typical in earlier investigations but also being seriously evaluated for use in laser-protection systems.

An additional application of operational performance and training relevance is the domain of virtual reality (VR) technologies. One subset of the issues to be investigated regards the accurate registration of size and distance relationships at near, intermediate and far virtual distances. No one can say to what extent misregistrations will adversely affect transfer of training. Since the initial candidate systems for applications of VR technologies are generally high-end, high-value systems with high return-on-investment potential, the negative transfer consequences carry correspondingly weighty implications. Such factors as levels of illumination, contrast, display optics, levels of detail, and Euclidean versus alternative rendering may affect the transfer from training to operational performance.

Regardless of the application, the univariable parameters presented and widely available, for example, in the Engineering Data Compendium (Boff and Lincoln, 1988), are inadequate. While providing superb points of departure, current sources simply do not provide answers in that part of the display envelope where the psychophysical meets the psychology of dynamic perception. This effort will expand that envelope.

THE HUMAN VISUAL SYSTEM

Capabilities and Components Overview

In comparative studies of visual systems, researchers have found an ingenious diversity of approaches in nature. These approaches help define boundary conditions and transformation mechanisms relating the array of light present in any given ecology to biologically significant, adaptive behavior on the part of living systems. The human visual system exemplifies one approach taken in biological evolution to deal with the problem of survival. Biological significance and evolutionary ecology define parameters for the biophysiological visual system each organism inherits (Bruce and Green, 1992).

A visual system is, at one level of analysis, a receiving and processing system, sensitive to a limited band of electromagnetic radiation (EMR). The array of EMR, as the input to a sensory system, may be characterized as having an angular extent and angular directions, frequencies or wavelengths, and temporal durations. The EMR that the human visual system senses is called light. Light, as is true of EMR in general, dependent on the medium through which it travels, undergoes varying degrees of absorption, diffusion, refraction, and reflection. These phenomena affect the amount and arrangement of light energy available to optical systems.

The human visual system is sensitive to EMR with wavelengths approximately between 390 nm (violet) and 700 nm (red). This system is capable of functionally discriminating thousands of frequency variations and combinations (seen as color or grayscale). Using an impressive combination of photochemical and mechanical adaptations, the human eye is capable of productive activity over eleven decimal orders-of-magnitude of light intensity (though at only about two orders at any given time according to Bruce and Green, 1992).

Eleven orders-of-magnitude translate to light intensities as low as about 0.000003 candelas/m^2 (cd/m^2, equivalent to Lumens/m^2/steradian or Lux/steradian) and as high as 300,000 cd/m^2. Human visual systems can discriminate objects with an angular separation as small as 0.5 min. of arc. Assuming intensities above threshold, we can resolve "clear" images of objects as near as one hand span and as far as the stars.

At a second level of analysis, the human visual system must process and be sensitive to the information originating in the visual array to effect adaptive and purposeful behavior. This view centralizes such concepts as data versus process limitations, bandwidth, feed-forward (anticipatory, template, or schema-based), feedback (reactive or filtering) systems, serial versus parallel, central versus distributed, and top-down versus bottom-up processing. In this view, the very real difficulty (interactive complexity) in

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dealing with distinctions between sensation, perception, and cognition must be addressed and seriously considered.

The critical components of the human eye include:

1. A *lens system*, consisting of the convex cornea and biconvex flexible lens, which executes powerful and essential convergence of light relative to the surface of focus on the back of the eye;
2. The *pupillary system*, with its curtain or shutter-like iris controlling the circular aperture, the *pupil*, which assists in the vernier regulation of effective light intensity. The aperture controls the amount and angular extent of light entering the egg-shaped, fluid-filled, main chamber of the eyeball. Pupil size critically defines the total surface of the flexible lens being accessed.
3. The *ocular vergence system*, controlled by a set of muscles (the pair of recti, the pair of obliques, and the superior levator) that coordinates the direction of gaze. The coordinated action of this set maintains clear binocular vision (individually convergent and mutually conjugate) on an attended object.
4. A *retinal system* that covers the posterior interior surface of the eye and constitutes the curved projection area for real images formed through the lens system. It includes the specialized sensor-receptor-processors and neural components to transmit coded information from the eye through the optic nerve.
5. The *postocular system* of neural pathways and visual data processing projection areas.

Beginning with simple biochemical photosensitive response elements, biological systems have diversified and cumulatively differentiated. This adaptive process effectively deals with such factors as physical media (air versus water or both), levels of illumination, and resolution requirements mediated by purpose and the extent and diversity of relevant ecologies. Bruce and Green (1992) present a compelling survey of ecologically consistent levels of visual system sophistication.

The Lens System and Accommodation

Basic structure and characteristics. Fairly far along in the evolution of visual systems came the biological synthesis of the lens or lens system. Human lenses in particular, among biological lens systems in general, constitute extremely effective optical systems despite numerous imperfections.

Lens systems uniformly bend (refract) light to form real and virtual images at specific distances from individual lenses and lens systems. The optics of image formation are fairly straightforward. An image is formed when rays of light coming from a corresponding point in object space arrive at one point on the image and converge there from all unobstructed points on the surface of the lens. Lenses receiving parallel light rays from an object in space project or form images at their *focal length* (f), defining the surface of exact focus. Points on objects at infinity reflect (or radiate or emit or generate or reradiate) photonic energy in all directions from the plane of incidence. From infinity, however, only rays from a point effectively parallel to and directed at the aperture have not diverged beyond the aperture to the lens in question.

Focal lengths change as a function of the shape/curvature of the lens or lens system for any given *index of refraction.* Index of refraction defines the ability to bend light, based on speed of EMR specific to the medium constituting the lens. Lens systems consist of several lenses that are roughly additive in total power. The shorter the focal length, the greater the *power* of the lens (its ability to bend light). Power, measured in *diopters* (D), is calculated as the reciprocal of the focal length in meters (f^{-1}). Increasing lens curvature, all else being equal, increases power. The power of a lens necessary to bend light rays to parallel (and, therefore, in focus for a second lens with a projection plane at its focal length) for an object closer than infinity is calculated as the reciprocal of its distance (d) from the lens in meters (d^{-1}). In fact, this "additive or corrective power" is most typically reported in the literature as the measured state of refraction.

The human eye is equipped with two primary lens subsystems with four refractive surfaces, affecting light through four refractive index fields, one of which is heterogeneous. The binocular visual array subtends as much as 220 deg. of visual angle in the horizontal plane. Only the central 120 deg. or so are truly binocular, the central 60 deg. of which are effectively chromatic. The exterior, peripheral 50 deg. on either side are ipsilateral monocular. Vertical extent is mechanically limited to about 50 deg. upward and 80 deg. downward relative to the axis. The entire array is initially converged through the outer lens (Wulfeck, Weisz, and Raben, 1958). Helmholtz (1867/1962, Vol. I, p. 93) commented:

> The eye is an optical contrivance of remarkably wide field of view, but it is only within a very limited part of this field that the images are clear-cut. The entire field is like a drawing which is carefully executed to delineate the most important central part of the picture, while the surroundings are simply sketched in, more and more lightly out towards the borders.

In the human lens system, the anterior lens, the **cornea**, contributes an essentially fixed value of optical power at between about 38 and 48 D in the population (Boff and Lincoln, 1988). It performs the critical task of converging light to enter the aperture (pupil) formed by the variable iris.

Changes in pupil size and location interact with the degree of convergence of the eyeball and the refractive power of the cornea to change the extent of the optical array or field of view.

The cornea itself is approximately 0.5 mm thick (Helmholtz, 1867/1962, Vol. I, p. 9) and constitutes the anterior sixth of the eyeball. The substance of the cornea is fibrous, tough, and perfectly transparent. Behind its two curved refractive surfaces is the aqueous humor filling the anterior chamber formed by the anterior surfaces of the iris and the flexible lens.

The posterior lens, called the *flexible or crystalline lens,* flexes to achieve maximum variable power across a range from about 16 to 32 D. The process whereby the human eye changes the shape and power of the crystalline lens is called *accommodation.* From birth through middle age the lens retains a significant degree of flexibility; it is, in fact, becoming more rigid, layered, and discolored throughout our lifespans.

The capsule surrounding the lens is flexible and, if unconstrained, would assume a much rounder, optically more powerful shape. Constant tonal tension is placed on the outer capsule of the crystalline lens by equatorial processes called the fibrils of zonal (also, zonules of Zinn or suspensory ligaments). The variable wall thicknesses of the capsule result in nested lens curvatures. A central anterior thinning makes this portion, within a few degrees of the visual axis (Alpern, 1969; angular dimensions measured from the foveal center of the retinal surface), capable of greater relative curvature and consequently greater optical power.

Paradoxically, as detailed by Koretz and Handelman (1988), the lens also becomes more rounded with age for any given object distance. This rounding normally would be associated with an increase in power. However, with age, apparently, an increasing fraction of a soluble Alpha-crystalline protein of the lens is converted into large, insoluble particles, reducing the index of refraction of the lens. The increasing curvature only partially (and less and less effectively) compensates for this progressively diminishing index of refraction.

The progressive, aging-based layering of the lens, in addition to mechanically instigating the greater curvature, mediates variable indices of refraction through the lens that, taken in isolation, should increase the overall index. However, this also eventually fails to compensate for the protein precipitation effects. The above would suggest that for any limiting value of ciliary muscular strength or tonus and suspensory ligament tension, the trend toward reduced optical power should be reflected in an outward shift in near point, far point, and measured tonic focus with age (as supported, for example, by the findings of Simonelli, 1979).

The ability to resolve detail at a variety of target contrast and luminance levels is called *visual acuity (Snellen acuity* being a clinically defined/ restricted subset). Visual acuity is greatest within a few degrees of the visual axis, corresponding to the above-mentioned corneal characteristic and

Helmholtz's comments. Degree of *retinal eccentricity* is measured as a retinal projection of visual angle, centered (at 0 deg.) on the fovea. As a point of interest, degree of *eccentricity* rapidly affects acuity (see section on the retinal system for elaboration). A fine-line object at threshold at the center of the visual field would have to be doubled in width to achieve threshold within as little as 6 deg. of the axis (Wulfeck et al., 1958).

Many objects to be resolved are closer to the lens system than optical infinity. Such objects propagate sensible divergent light rays that enter the lens system. Lenses of greater power are needed to focus nearer objects. Conversely, less power (longer focal length) is needed as objects recede toward infinity.

Human lens systems are biologically evolved and produced. In the resulting variation, some lens systems are capable of even longer focal lengths than are needed to focus parallel rays on the retina. When these lenses present at or near such extremes, measurement instruments calibrated to optical infinity will render negative dioptric readings. When this happens it is often and confusingly referred to as focused "beyond optical infinity." In reality, "focused behind the retina and blurred at the retinal surface" would be a more correct description.

A smooth muscular process, the ciliary body, configured with at least three muscular orientations (see discussion by Benel, 1979) surrounds the lens and contracts in accommodation through the action of the oculomotor (third cranial) nerve. This primary efferent path originates through the nuclei of Edinger-Westphal in the pretectal nuclei just anterior to the superior colliculi. Ciliary contraction counters the tension from the fibrils of zonal and frees the myopic elasticity of the lens capsule to thicken the lens for (more dioptrically positive) near accommodation. The thickening of the lens incidentally causes a forward displacement of the iris, very slightly expanding the effective field of view for any given pupil size, and a proportional posterior displacement of the optical center of the lens system. Relaxation of the ciliary process reverses these outcomes permitting zonular tension to flatten the lens, reducing its optical power for far accommodation and causing corresponding displacement and iris effects.

There is considerable anatomical variation in human eye axial length, ranging from roughly 21 mm to 26 mm. This total depth results in effective eye depths between about 14.7 mm and 18.2 mm (Boff and Lincoln, 1988; estimates apparently based on a fixed state of accommodation). Smith, Meehan, and Day (1992) point out that the equivalent eye depth is not actually fixed, but, *in sum*, increases slightly with increasing focal length (see also Helmholtz, 1867/1962, Vol. I, p. 169, for displacement magnitude estimates). So, the human eye embodies a lens system that moves slightly relative to its projection surface, the retina.

Another relevant phenomenon attributable to anatomical variation is *myopia*, generally associated with eye depth too great to permit accommodation on objects farther away than about one meter. An eye with the same lens system as a normal healthy eye but with an eye depth 2 mm greater, for example, might not be capable of achieving retinal focus for objects beyond about 30 cm. Despite a maximally "flattened" lens, farther objects result in clear images projected short of the retina, out of focus at the retina. *Hyperopia* is generally associated with eye depth too shallow to allow retinal focus of objects nearer than about a meter. Despite a maximally "fattened" lens, nearer objects result in focused images projected beyond the retina. These variations in eye depth interact with differences in normal, healthy accommodative lens systems (with different optical power characteristics), adding individual differences in both the clarity of focused images and range of accommodation.

To establish a frame of reference and a nominal eye to support further discussion, a reference focal length (*f*) has been selected. Maskelyne (1789) used about 16 mm; Asimov (1988) estimated about 16.5 mm; Smith, et al. (1992), Boff and Lincoln (1988), Kling and Riggs (1971), and Wulfeck et al. (1958) used about 17 mm. The value selected here, based on Emsley (1939) at 16 2/3 mm, conveniently places the total power of the lens system of the nominal eye at 60 D when focused for infinity. Performance relationships for this nominal eye are summarized in Table 1.

Table 1 shows that this nominal eye varies its focal length from 13.7 to 17.5 mm to focus from +12 D (8.33 cm) to -3.0 D, respectively. These values mean that the total lens system power varies from 73.2 D to 57 D for a range of 16.2 D. Accommodating to 57 D for an object at optical infinity would place the plane of exact focus about 0.8 mm behind the nominal retina. This would result in a large blur circle (for each point on the object) at the retinal projection surface. As stated earlier, when precisely focused on an object at optical infinity, the power of this nominal eye lens system is 60 D, and the corresponding focal length equals the equivalent nodal depth of 16 2/3 mm.

Virtually all ophthalmological and most psychological investigators have used an object-oriented metric, corrective D, to report the accommodative state of the human eye. These measures, which represent the power of a lens needed to collimate the light leaving the lens, are the reciprocal of the distance to the object in meters. The added power needed to focus the image on the retina is "left out." Lens system diopters (the reciprocal of lens focal length) are based on the assumption of parallel rays and may be estimated for objects "not at infinity" by adding the reciprocal of the base lens focal length to the corrective D associated with a selected object distance.

The nominal eye was specified to reflect a wide range of focal lengths adjusted (by linear approximation) to represent the shift in principal points detailed by Smith et al. (1992). Further adjustments are presented that estimate the effects of a separate but complementary phenomenon referred to as retinal stretch (see discussion of the relevant findings of Blank and Enoch (1973) and Enoch (1973) in a later section, *The Retinal System*).

Table 1. Specification of a nominal eye. Representative estimates of component optical power to image size relationships with proportional retinal stretch adjustments for selected object distances.

Nominal LENS + CORNEA OPTICAL POWER DISTRIBUTION FOR VARIOUS OBJECT DISTANCES:

(Adjusted for monotonic increase in effective projection distance and for retinal stretch with baseline at infinity focus (f =16.66 mm))

Object distance,d, in m or Dioptric value when negative	Total lens system effective focal length,f, in m.	Opthalmic Diopters, D=1/d, for d < infinity; D=given,for negative values	Flexible Lens power in D	Effective Corneal power (k) in D	Total Lens System Power (1/f) or given for negative D	Est of Effective Image Projection Distance to retina adjusted for shift with accommodation	Est Retinal Image Size (RIS) in m based on accommodation-mediated changes in projection distance	Est of RIS relative to unity object (1 degree visual angle)at infinity	Estimated # of cones engaged by circular object adjusted for estimated magnification & retinal stretch	Estimate of Total % Change in cones engaged resulting from accommodation & retinal stretch
.083	.0136566	12.000	32.224	41	73.224	.0163333	.000285099	.980000	9990.7220	-7.0717
.090	.0138421	11.111	31.243	41	72.243	.0163580	.000285530	.981481	10045.8067	-6.5593
.100	.0140811	10.000	30.017	41	71.017	.0163889	.000286069	.983333	10114.9380	-5.9163
.200	.0152662	5.000	24.504	41	65.504	.0165278	.000288493	.991667	10429.8337	-2.9873
.300	.0157063	3.333	22.669	41	63.669	.0165741	.000289302	.994444	10536.1894	-1.9981
.400	.0159360	2.500	21.751	41	62.751	.0165972	.000289706	.995833	10589.6292	-1.5010
.500	.0160770	2.000	21.201	41	62.201	.0166111	.000289948	.996667	10621.7771	-1.2020
.600	.0161724	1.667	20.834	41	61.834	.0166204	.000290110	.997222	10643.2441	-1.0023
.700	.0162412	1.429	20.572	41	61.572	.0166270	.000290225	.997619	10658.5948	-.8595
.800	.0162932	1.250	20.375	41	61.375	.0166319	.000290312	.997917	10670.1172	-.7523
.900	.0163339	1.111	20.222	41	61.222	.0166358	.000290379	.998148	10679.0847	-.6689
1.000	.0163666	1.000	20.100	41	61.100	.0166389	.000290433	.998333	10686.2622	-.6022
2.000	.0165153	.500	19.550	41	60.550	.0166528	.000290675	.999167	10718.5995	-.3014
3.000	.0165654	.333	19.367	41	60.367	.0166574	.000290756	.999444	10729.3926	-.2010
4.000	.0165906	.250	19.275	41	60.275	.0166597	.000290797	.999583	10734.7918	-.1508
5.000	.0166058	.200	19.220	41	60.220	.0166611	.000290821	.999667	10738.0322	-.1206
6.000	.0166159	.167	19.183	41	60.183	.0166620	.000290837	.999722	10740.1928	-.1005
7.000	.0166231	.143	19.157	41	60.157	.0166627	.000290848	.999762	10741.7362	-.0862
8.000	.0166286	.125	19.138	41	60.138	.0166632	.000290857	.999792	10742.8939	-.0754
9.000	.0166328	.111	19.122	41	60.122	.0166636	.000290864	.999815	10743.7944	-.0670
10.000	.0166362	.100	19.110	41	60.110	.0166639	.000290869	.999833	10744.5148	-.0603
100.000	.0166636	.010	19.011	41	60.011	.0166664	.000290913	.999983	10750.3514	-.0060
1000.000	.0166664	.001	19.001	41	60.001	.0166666	.000290917	.999998	10750.9351	-.0006
1E+100	.0166667	0.00	19.000	41	60.000	.0166667	.000290918	1.000000	10751.0	.0000
infinity-1D	.0169492	-1.00	18.000	41	59.000	.0166944	.000291403	1.001667	10815.9911	.6045
infinity-2D	.0172414	-2.00	17.000	41	58.000	.0167222	.000291887	1.003333	10881.2359	1.2114
infinity-3D	.0175439	-3.00	16.000	41	57.000	.0167500	.000292372	1.005000	10946.7349	1.8206

Adaptations of Emsley eye, H.H., 1939, Visual Optics (2nd Ed) London: Hatton Press, in Boff and Lincoln (1988) & findings from Blank and Enoch (1973) .

The specification of a nominal eye provides a statistically and conceptually convenient referent for a person-centered view of the eye and its relationship to human visual perceptual phenomena. The values used provide a logical and anatomically representative way to deal with the negative dioptric values commonly reported by researchers in this area. Two convenient options are: the nominal dioptric power of the total eye system, always positive at 60 $\pm$ some value equivalent to the traditional dioptric values, or a projection-distance-based estimate of either the extent of the retinal image or its area. Both of these approaches provide statistically efficient and psychophysiologically consistent metrics for analysis.

Due to anatomical variation, individuals with normally functioning eyes may focus accurately to infinity while their lens systems are at power values anywhere from about 68 D to 55 D, corresponding mainly to differences in axial eye length mentioned earlier. The actual individual range of dynamic focus varies significantly in the normal population. Performance ranges from virtually no ability to change lens power among very old people to the impressive 16+ D range found among a limited number of gifted young people and arbitrarily assigned the nominal eye. When appropriate for clarity, dioptric measures given in this report will reflect reference to the nominal eye.

Three critical and interdependent factors bear on the interpretation of clinical and experimental measurements of accommodation. They are eye depth, the optical dynamics of the lens system, and stimulus quality. Any two eyes with identical optical dynamics but different depths will produce different refractive measures while each is accurately accommodated to the same object. The same is true for holding eye depths equal while varying the stimulus quality or optical limits and tonic characteristics of the lens system. It is an important fact, central to the psychology of visual accommodative behavior and its correlates, that the actual distance of accommodation often does not correspond to the distance to the object (see seminal discussions in Adamson and Fincham, 1939, and Ittelson and Ames, 1950).

Imaging and blur processing. In the human visual system, there exists a zone on either side of the precise plane that contains *planes of acceptable focus*. For all practical purposes, the image is "focused enough" anywhere in this zone given the level of resolution *needed* at the image plane. Helmholtz (1867/1962, Vol. I, p. 123) credits J. Czermak as naming "...that segment of the visual axis where, for a given state of accommodation, an object can be seen without being indistinct...the 'line of accommodation'." In the same reference, Helmholtz points out that the length of this segment increases with distance from the eye, becoming infinite when its distance is very great.

The existence of a "plane of exact focus" is only hypothetical and subject to several assumptions and simplifications. Among these is the fact that white light, typical daylight, is composed of a spectrum of colors. Each of these colors (corresponding to wavelengths of EMR) is refracted differentially through each changing medium in the eye. The *chromatic aberration* that results translates into a focus error of as much as 2.5 D between the violet and red ends of the visible spectrum (Bedford and Wyszecki, 1957, in Boff and Lincoln, 1988). This means that if the eye is (most typically) optimized for the yellow-green light from a source, the violet and red components will be out of focus at the retina. They are in exact focus before and behind the retina, respectively, by more than 1.0 D. Fincham (1951) clearly implicated chromatic aberration as a critical factor for a majority of individuals, enabling them to initiate any response and in the correct direction to compensate for experimentally induced blur. It might be argued that certain prevalent oscillations in focus discussed later may be implicated as agents in this connection. Wald (1967) speculates that the absence of blue-sensitive photoreceptors at the very center of the fovea and the yellowish pigmentations of both the flexible lens and the central fovea may largely compensate for the effects of chromatic aberration.

Kruger and Pola (1987) measured changes in accommodation while they manipulated lens-induced blur, target size, and availability of chromatic aberration information independently and in combination. Their high-contrast targets traversed a range of optical and actual distances based on a sine-wave forcing function (manipulated at 7 temporal frequencies between 0.05 and 1.0 Hz). The distances were 100 to 33.3 cm, 2 to 6-deg. visual angle, or 1.0 to 3.0 D, respectively.

They found that, within the limits traversed, all three variables had significant effects, both individually and additively. For the baseline, size-only manipulation, the phase lag was generally least, and the response amplitude was about half the effect of the full manipulation. The blur manipulation accounted for the majority of the remaining response amplitude, but chromatic aberration information added a consistent, if small, component. This monocular study did not address possible effects related to convergence or the changing apparent target proximity or the predictability of the forcing function.

Spherical aberration is an imperfection in the image that results from rays of the same wavelength coming from different points on the lens failing to converge to the same point. This error increases as a direct function of effective aperture diameter because new parts of the lens with (effectively) different focal lengths are exposed as the aperture increases. This aberration reduces contrast sensitivity and emerges as a factor to be considered at pupil diameters greater than 3 mm, estimated to effect blur equivalent to about 1.5 D in depth of field at a 6 mm pupil diameter (Charman and Whitefoot, 1977).

Contrast refers to the difference in values of luminance between adjacent array components or fields. Contrast is sometimes defined as *modulation* (m), where, in periodic stimuli, L_{max} is maximum luminance in a pattern and L_{min} the minimum luminance:

$$\mathbf{m} = \frac{L_{\max} - L_{\min}}{L_{\max} + L_{\min}} \tag{1}$$

Sensitivity to contrast is often used as an alternative measure of acuity. Contrast sensitivities are measured as reciprocals of threshold contrast values. Independent measures of contrast sensitivity are most typically reported for sine-wave gratings of different spatial frequencies.

Adamson and Fincham (1939), in their study of the effects of lenses and convergence on accommodation, inserted incremental corrective lenses in the optical path while measuring refraction. Their study broke new ground in that it isolated physiological tolerance to changes in refraction ("light vergence changes") from reported "perceptual" clarity of focus. They found an approximate 0.25 D "dead zone" on either side of expected values (see Figures 1 and 2) within which accommodation (lens power) did not change for targets across a variety of distances (14.7 mm to 18 m).

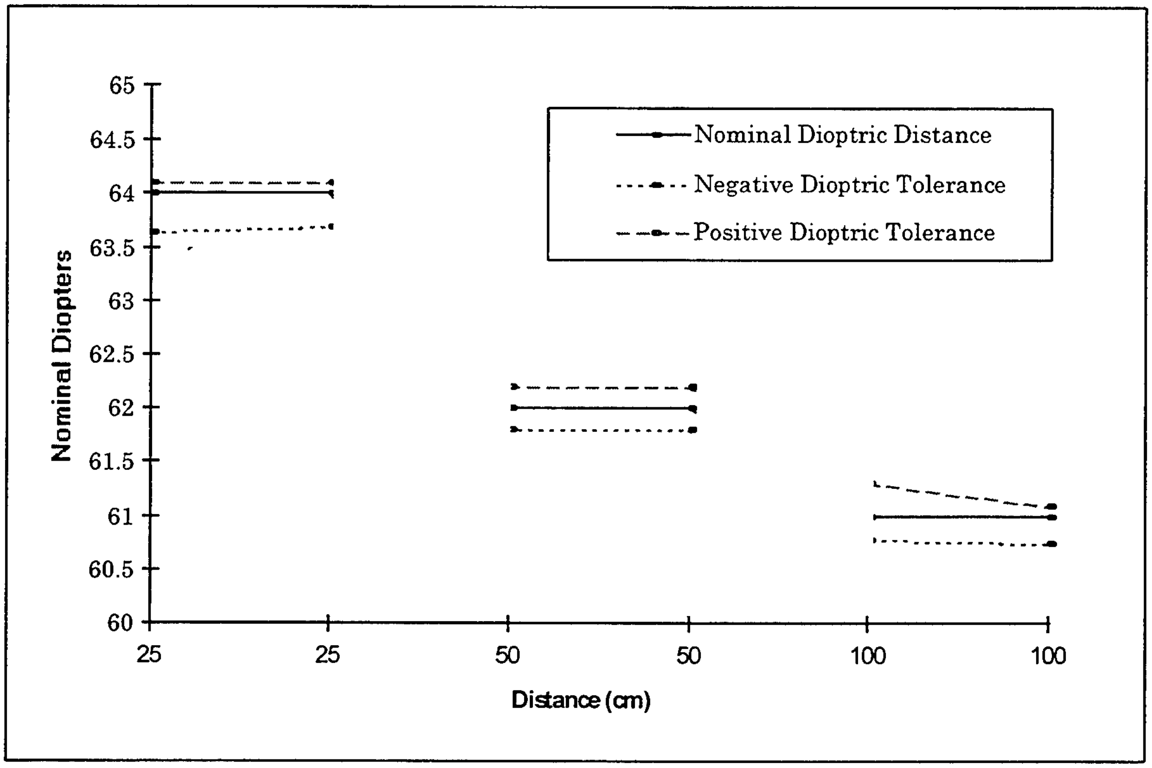

Figure 1. Dioptric limen or "dead zone" for two subjects at three distances as reported by Adamson and Fincham (1939), Table II.

They found this accommodative limen zone to be slightly smaller in monocular viewing. Additionally, they observed that pupil size fluctuated erratically under monocular viewing conditions while virtually not at all in binocular viewing. They further reported that binocular viewing also stabilized accommodative states "very considerably."

Because light rays converge to the image surface and diverge beyond it, a geometric representation of the zone described above is an hourglass-shaped conical arrangement with its "waist" at the surface of exact focus and its

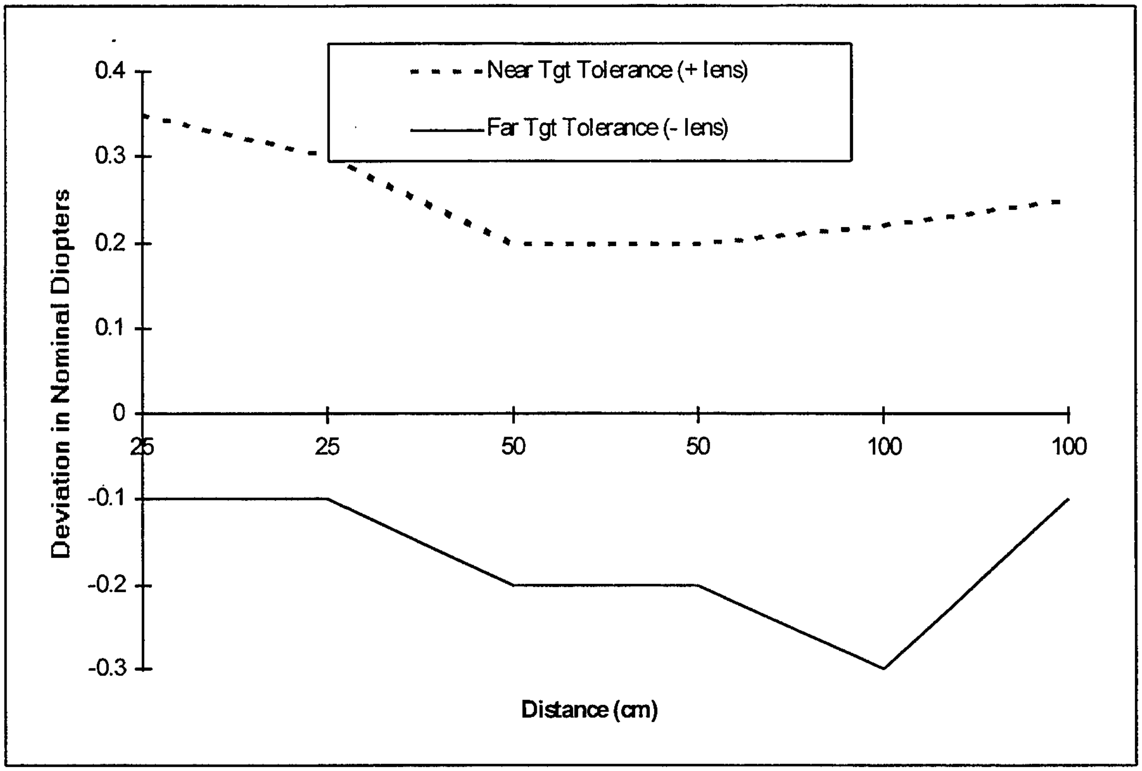

Figure 2. Binocular dioptric difference limen for two subjects at three distances based on Table II from Adamson and Fincham (1939).

longitudinal axis perpendicular to it. The accommodative dead zone would suggest that the waist is extended along the visual axis. Surfaces normal to the central axis of this hourglass, therefore parallel to the surface of exact focus, cut the conical shape to form blur circles. The larger the circle, the greater the blur, and the less likeness to the image at the surface of exact focus (see Figure 3).

Campbell (1957) reports a perceptual depth of focus (based on subjective blur-awareness) nearly twice the size of Adamson and Fincham's (physiological) dead zone associated with an (often unperceived) accommodative reflex. The human visual system is apparently "robust" or insensitive to significant degrees of blurring. As can be readily deduced, a family of focal lengths can place an image in the zone of acceptability; this zone is here referred to as *depth of focus*. Applying the same logic but holding the focal length constant, there is a zone of object distances on either side of the precise object distance for a given focal length that results in an image within the zone of acceptability. This zone (in the visual array's object space) is the *depth of field*, effectively the specific length of Czermak's line of accommodation.

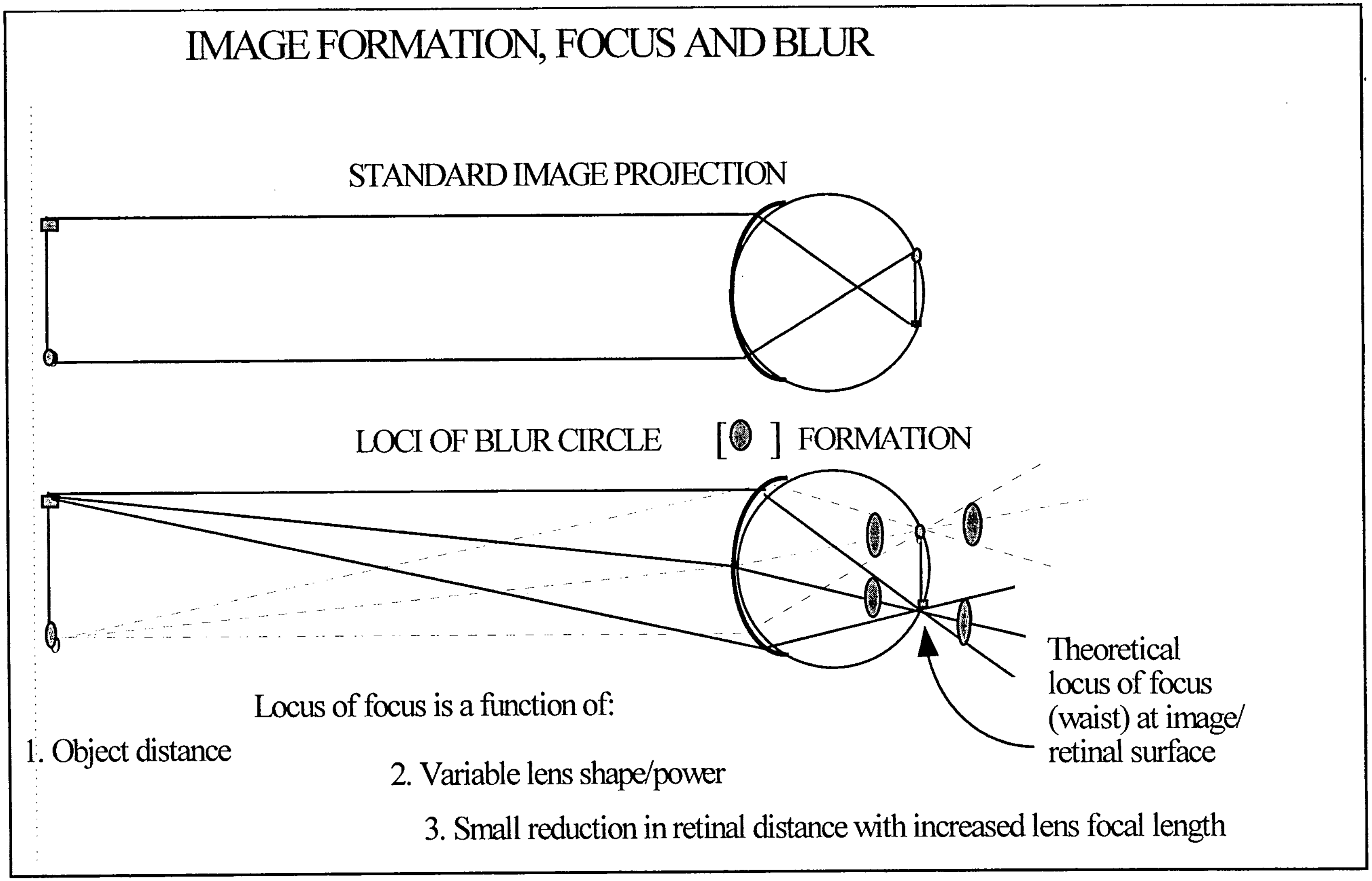

Figure 3. Illustration of blur circle formation.

Fisher (1977) reported that the dynamic range of accommodation diminished approximately linearly with age, from a mean of approximately 11 D in 15-year-olds to approximately 1 D in 55-year-olds. He clearly demonstrated that while the lens became more rigid **with age**, the ciliary **muscular force being exerted to achieve the relevant dynamic range increased** (see Figure 4). Muscular force increased by approximately 50 percent through the mid-forties, dropping off slowly thereafter. He developed a force coefficient based on age that reliably predicted accommodative amplitude.

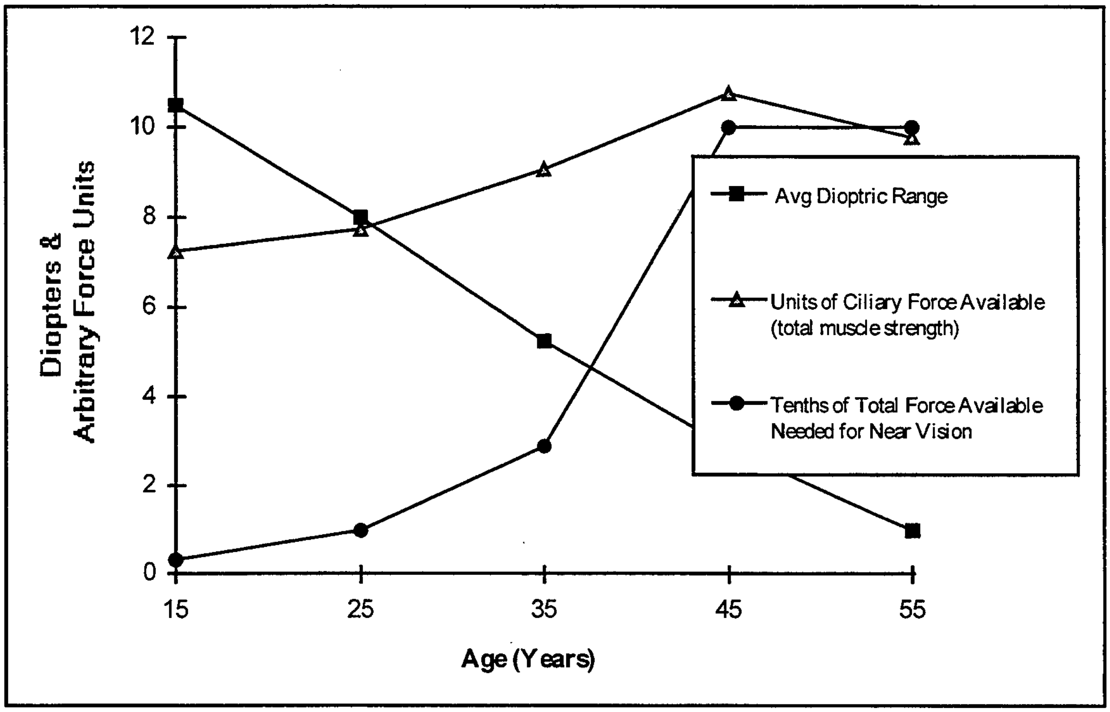

Figure 4. Fisher (1977) demonstrated that total ciliary strength available increases with age through the mid-forties, then slowly declines. The percentage of available ciliary strength demanded for near vision increases to (then stabilizes at) 100 percent of available force during the same period.

Components of accommodation. Ciuffreda (1991) refers to four (not necessarily voluntary) components of accommodation, the interactive forces involved in driving the accommodative subsystem. They are reflex accommodation, proximal accommodation, convergence accommodation, and tonic accommodation.

Reflex accommodation refers to blur and contrast optimization acting as a negative feedback mechanism to optimize focus. Campbell (1954) confirmed that the reflex is activated only when stimulus luminance is near and above the lower limit of foveal cone threshold for visibility. Fincham (1951) reported that the reflex operated effectively within about 2 D of exact monocular focus for subjects up to an age of about 26 years. Beyond 2 D and/or at ages greater than 26 years, Fincham found that "the response is no longer involuntary (p. 383). This reflex operated when all cues to distance were experimentally removed. Further attempting to resolve the underlying mechanisms, Fincham (1951, p. 386) evaluated chromatic aberration as a stimulus to accommodation and noted that:

> It is perhaps remarkable that red and blue objects placed at the same distance from the eye do not appear by monocular vision to be at different distances since the light from them is focused in different planes in the region of the retina. It appears there must be some compensating sense by which color differences are correlated with vergence differences and thus the brain accepts the fact that the eye is relatively hypermetropic to red and myopic to blue.

In his subsequent studies alternating between white and monochromatic light sources, Fincham found that about two-thirds of his subjects used some degree of chromatic information along with contrast clarity to focus more accurately. He also found that, regardless of light chromaticity, accommodation tended to stay at a value for a given target fixation in spite of otherwise effective blur manipulations (up to about 0.75 D). This condition prevailed until the subject was directed to shift (attention) away from the target. This reflected an apparent "fixation lock" or accommodative inertia (lag) linked to target fixation.

Charman and Jennings (1979) investigated the appropriateness of using annular artificial pupils in studies of the initial direction accuracy of accommodative correction to blur. Annular pupils introduce a "pupil obscuration ratio", E, defined as the ratio of the inner to the outer diameter of the annulus. Experimental confirmation of theory has shown, according to the authors, that the depth of focus with an annular pupil is increased by a factor of $(1 - \mathsf{E}^2)^{-1}$ when compared to a normal pupil of equal outer diameter. Increasing depth of focus given a fixed object under fixed illumination conditions reflects a diminishing sensitivity to blur or independent reduction in the size of actual blur circles and, necessarily, a reduction in acuity. Depth of focus with an annular pupil is **equal** to the **depth of focus** for a pinhole of **equal** total unobstructed **area**.

This seems reasonable given the relationship discussed earlier relating acuity to eccentricity, since the obscurations in annular pupils block direct rays to the fovea and increase the obliquity of rays impinging the retina. One would expect, therefore, when using annular pupils, that acuity, specified by changes in the *ocular modular transfer function* (an index of how well spatial intensity and contrast modulation are transferred through an optical or imaging system), would be degraded at optimum focus. This turns out to be true for a range from low to moderately high spatial frequency stimuli relative to equal-area standard artificial pupils. Campbell and Westheimer (1959), who employed annular pupils to eliminate focal asymmetry due to spherical aberration, found that **none** of their subjects was able to respond infallibly in initial direction of blur correction using annular pupils. All, however, responded infallibly with standard pupils of the same (4 mm) outer diameter.

Alpern (1969) studied the low amplitude oscillatory behavior of otherwise "steady state," closed-loop accommodation. He offered telling evidence that this oscillatory behavior supports reflex accommodative performance. He argued that the oscillations, dominant at 2 Hz, permit sensitivity to decreases in contrast on either side of the current refractive state up to about 1.25 D (approximating Fincham's, 1951, 2 D range). Beyond this level (dioptric limen) of initial blur (refractive error), a number of investigators have found no effective or consistent blur-driven (reflexive) response.

Legge, Mullen, Woo, and Campbell (1987) discuss a phenomenon referred to as *spurious resolution,* eliminating it as a factor relating effects of spatial frequency on functional depth of focus. Out of focus optical images present distorted representations of higher frequency components. These images offer false impressions of higher frequency detail at apparent contrast reversals. A similar phenomenon permits the impression of detail on objects whose real details exceed the resolving power of the optical system in question. For example, the apparent details we perceive on the full moon are a blatant (apparently detailed) misrepresentation of gross features on the surface of that distant body.

Legge et al. demonstrated that functional depth of focus increased with reductions in spatial frequency, increases in stimulus blur, and decreases in visual acuity among tested subjects. Lower spatial frequency (1 cycle per degree) targets with large pupils (8 mm diameter) produced defocus response functions very like the response functions for a spatial frequency in the range near optimum contrast sensitivity (3.5 cycles per degree) when coupled with a small (1 mm) pupil diameter. In other words, if we define high *focal demand* as stimulus conditions that encourage effortfully accurate accommodation for object distance, small pupil diameters effectively counter the demand, mimicking the effect of low focal demand stimuli. At constant pupil diameter, lower spatial frequencies generally increase defocus tolerance. At constant spatial frequency, pupil diameters smaller than about 2.5 mm also generally increase defocus tolerance, operationally defined as increased depth of focus measured against standard acuity tests.

Legge et al. point out that the retinal image of a sine-wave target closely approximates a sinusoidal intensity distribution and that defocusing effectively reduces image contrast, more so the higher the spatial frequency. They demonstrated a greater sensitivity to focus error (therefore reduced depth of focus or higher focal demand) for horizontally versus vertically oriented gratings. Further, as illustrated in Figure 5, they related the kind of low-pass filtering effects of blurring at differing spatial frequencies to standard acuity measures. Finally, they demonstrated that adding filters to the visual path effected an increase in the apparent depth of focus, decreased sensitivity to exact focus, and increased the spatial frequency at which spurious resolution took place.

Latency of accommodation is approximately 0.37 seconds (Campbell, Robson, and Westheimer, 1959; Campbell and Westheimer, 1960) with latency up to 0.425 seconds for non-repetitive stimuli and as low as 0.22 seconds for repetitive signals (Carter, 1962). Campbell and Westheimer (1960) presented response profile evidence suggesting that accommodation is a continuously monitored behavior, as distinct from the ballistic pattern of saccadic movements, capable of stimulus-based modification within reaction

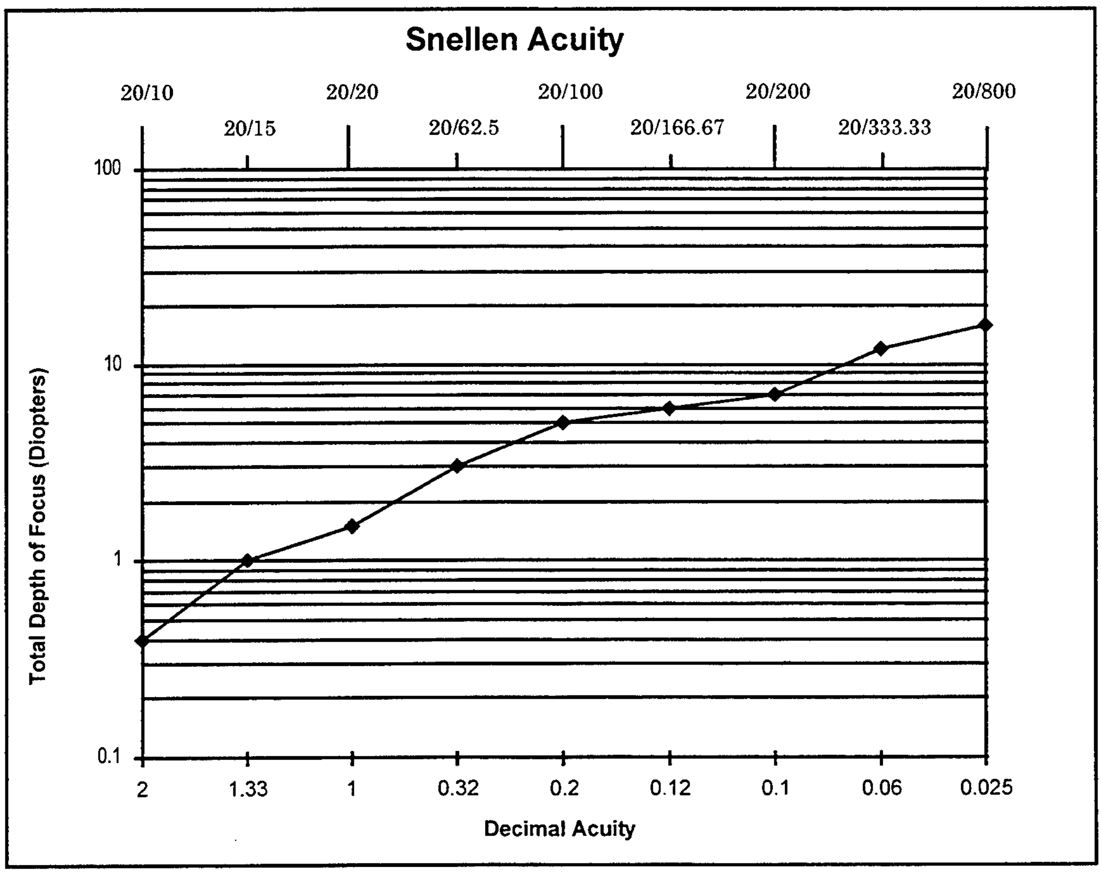

Figure 5. Total depth of focus (total range) predicted for individuals with normal vision when image is blurred to the acuity performance level indicated. For example, a person with normal vision should be able to tolerate about $\pm$ 3.5 D (7 D total depth) of refractive error and still accurately resolve the 20/200 Snellen row. Based on dilated pupil data compiled by Legge et al. (1987, Figure 10).

and response time limits. Stimulus changes inside normal latency periods result in response profiles reflecting (step) event durations as short as 0.1 seconds.

Consistent with a recent unifying theory of oculomotor control, Hung and Ciuffreda (1988) present evidence for a dual-mode control process for accommodation. The phenomenon combines a preprogrammed, ballistic, open-loop response component and a slower-latency buffered-response component with the fast closed-loop feedback characteristic described above. Ballistic or step-response forms were associated with rapid stimulus focal demand changes (≥ 2.5 D s^{-1}) and a ramp or continuous response form with slower changes. Subjects presented hybrid step-ramp response patterns at intermediate focal demand change velocities.

Proximal or psychic accommodation emerges when an individual anticipates or reacts to a very near object with a rapid increase in accommodation. This accommodation component implicates higher-order, anticipatory, and experience-based vectors. For the experimental psychologist or instructional technologist, this component highlights the criticality of instructions on response profiles regardless of otherwise well controlled stimulus conditions. A number of investigators have confirmed that response latencies can be shortened by as much as 50 percent with predictable periodic stimuli.

Convergence accommodation is an incidental component induced by ocular vergence to maintain binocular fusion. This will be discussed later in the section on ocular vergence.

It has long been established that the primary innervation agent for contraction of the ciliary body is the parasympathetic nervous system (PNS). There has also existed a growing body of (no longer controversial) evidence that the sympathetic nervous system (SNS) is a generalized agent in extension (Cogan, 1937; Toates, 1972; Gilmartin, 1986). Jose, Polse, and Holden (1984), in their 3rd chapter, provide a concise discourse on both the pharmacological and anatomical specifications bearing on both the PNS and SNS innervations of the human visual system.

In brief summary, the PNS innervating the iris (for pupillary constriction) and the ciliary body originates centrally in the midbrain in the Edinger-Westphal nuclei, traveling through the third cranial nerve. This nerve, also called the oculomotor nerve, is the long preganglionic nerve that synapses in the ciliary ganglion with the short postganglionic nerves affecting the iris and the ciliary body. Smooth muscle units in the iris and ciliary body contain muscarinic receptors for acetylcholine. Contraction occurs when the receptors are activated.

The SNS processes that innervate the dilator muscle of the iris and, presumably, beta receptors in the ciliary body, originate in the hypothalamus. The first-order neuron goes from there to the ciliospinal center of Budge-Waller to synapse with the preganglionic neuron. This neuron runs first along the internal carotid artery to reach and enter the nasociliary nerve and then with the short and long ciliary nerves to the eye. Sympathetic stimulation results in norepinephrin release to stimulate, in the case of the ciliary body, beta receptors resulting in a reduction in aqueous production. The more traditional antagonistic relationship between PNS (stabilization) versus SNS (activation) innervation would make simple an explanation of the recent and repeated confirmation of a **tonic accommodation**.

Tonic accommodation or focus, also called dark, empty-field, or resting focus, defines a focal length configuration of the crystalline lens and, thereby, the overall lens system of the human eye under unstimulated or occluded open-loop conditions. Tonic and dark focus are generally measured under conditions of homogeneous field and no light or very low light levels and, often, after some variable period of dark adaptation. However, empty field and resting focus are more typically associated with homogeneous visual arrays at photopic levels of illumination (referred to as *Ganzfeld*).

The classical view, too frequently still taught in basic texts (see Proctor and Van Zandt, 1994, for a refreshing exception), held that the human eye, at rest, focused to optical infinity. As demonstrated and accepted in serious ophthalmological, physiological, and psychological literature over the last half century, the unstimulated human eye is typically in "homeostasis" or tonic balance at a much closer distance for university students (Leibowitz and Owens, 1978) and somewhat more distant but still well short of optical infinity for military recruits (Simonelli, 1979).

It is only fair to note that a careful reading of the great master, Helmholtz, reveals that his always careful studies and observations, at least initially, affirmed that most individuals have a far point of accommodation significantly "closer than infinity." It was his formidable English version translator, the physicist Southall, who, with the benefit of at least an additional 70 years of scientific "progress," discounts Helmholtz's discussions in this direction (Helmholtz, 1867/1962, Vol. I, p. 128). Southall emphasizes Helmholtz's supplement for his 3rd edition, where he specifically refers to infinity focus as the relaxed state of the normal eye.

Tonic focus has been measured at optical powers consistent with object distances in a distribution centered at about 0.6 m (61.67 D, nominal). Studies of tonic focus have shown it to be reasonably stable within subjects. Miller (1978) presented results correlating measured dark focus on consecutive days at between 0.95 and 0.85, and morning-evening correlations at 0.78. Hull, Gill, and Roscoe (1982) reported 0.9 or better. Leibowitz and Owens (1978) report correlations between dark, resting, and empty field accommodation between 0.84 and 0.68, while they also report retest measures of resting focus to vary about + or -0.25 D.

Krumholtz, Fox, and Ciuffreda (1986) compared diurnal variations in tonic focus under normal viewing conditions versus extended periods in total darkness. They found small and non-systematic diurnal variations in tonic focus (means ranging from 0.5 D to 1.1 D) and high reliability ($r > 0.9$). In contrast, extended periods (1.5 to 2 hrs.) in total darkness resulted in large excursions in measured tonic focus (mean range shifting upward from 0.6 D to 2.5 D), spanning the majority of individuals' respective accommodative ranges, with a generally increasing (myopic) trend. Any very brief exposure to normal light or cue conditions reinstated normal tonic responses.

Otero (1951), citing a veil of secrecy delaying publication of relevant military-related research during WWII, provided evidence for the dominant contribution of accommodation to nocturnal myopia as compared to the much smaller cumulative effects of spherical and chromatic aberrations. *Nocturnal or night myopia* is characterized by a sustained and often detrimental state of over accommodation during conditions of reduced stimulation. In the process of his research, Otero accumulated compelling 2nd Purkinje image photographic evidence for a night or resting accommodation to about 0.8 m.

He further cited earlier work on minimum illumination acuity functions (Otero and Duran, 1941) demonstrating that threshold acuity at the lowest illumination seemed to occur near an individual's "state of rest" of accommodation. A more formal confirmation of this last observation is presented by Johnson (1976), defining the threshold of illumination for regression to tonic focus below 0.51 cd/m^2 and at or above 0.051 cd/m^2, very near the lower bound of mesopic vision. Johnson's data indicate that, for any given level of illumination, peak acuity occurs at or near tonic focus and that errors in accommodation account for virtually all reductions in effective acuity at any given stimulus distance.

Heath (1956) conducted a series of experiments that related degradation in acuity to the closely related closed-loop phenomenon of nocturnal myopia, associated with increased accommodation of 1.5 to 1.75 D. He proposed that the loss of acuity associated with night myopia was more directly related to the reduction in effective contrast than to lower illumination.

Heath's critical control was the maintenance of photopic light levels as he used optical lenses, lacquered filters, and ground glass plates to blur the stimulus targets at a variety of optical distances from 16.6 cm to infinity. High clarity target conditions resulted in accurate accommodation. He found that the lower the stimulus clarity the lower the slope of the response function (reduced accommodative amplitude) approaching zero for the "shadow" (total blur) condition. The change in slope of the typically ogive-shaped function pivoted around accommodation levels at 0.5 to 1.75 D. The mean tonic focus for his study was 1.25 D (0.8 m on average, corresponding to 61.25 D nominal).

These values were consistent with tonic levels and the empty field average of 61.16 D nominal reported by Whiteside (1957), who concluded that blurring reduces the gradients of contrast within the image and consequently reduces the stimulus to reflex accommodation. Heath further argued that his findings implicated reduced effective contrast (contrast sensitivity) rather than reduced illumination levels as the primary stimulus for the reflex accommodation effects observed. Interestingly, he also reported that accommodation (lazily) lagged stimulus distance changes (both up and down). It tended to stay at the current level of refractive state until "asked" to shift fixation, demonstrating an accommodative inertia (the so-called "lead" and "lag" of accommodation). Morgan and Olmsted (1939) were among the earliest to comment on the measured lead and lag of accommodation with respect to clear focus for a given object distance. Fincham (1951) relates this lag to the adequacy of stimuli to reflex accommodation discussed earlier.

Gilmartin and Hogan (1985a, p.1025) echo the long established fact that the ciliary muscle, the primary effector of accommodative action, responds primarily to parasympathetic inputs. This "input is mediated by the action of acetylcholine on muscarinic receptors and ... the excitatory phase of this interaction initiates positive accommodation." Investigating the extent of sympathetic nervous system involvement, they compared selected drug effects on the maintenance of tonic focus. Two beta receptor (SNS-influencing) drugs, **timolol maleate** (antagonist) and **isoprenaline sulfate** (agonist), had no effect on pupil size. Timolol effected a 0.85 D myopic shift in tonic accommodation (TA), while isoprenaline induced a 0.47 D hyperopic shift. Neither drug affected the distribution of TA for their respective samples. **Tropicamide** is a PNS excitatory inhibitor, a muscarinic receptor antagonist. Its application effected a small increase in pupil size (understandable given the dark adaptation conditions prevailing). It also resulted in a dramatic 1.24 D hyperopic shift in TA and a complete disruption of the premanipulation TA distribution. Together these results clearly implicate the PNS as the primary agent in defining individual differences in TA based on ciliary muscle tone. There are large individual differences in TA reported across a variety of sample sizes as illustrated in Table 2.

Ebenholtz and Zonder (1987) demonstrated that closed-loop focus at accommodative extremes (near and far) has a temporary biasing effect on the locus of both tonic focus and near point of focus. They called this phenomenon *accommodative hysteresis*. They induced an average shift of 0.62 D inward and 0.37 D outward in near point (NP) with an 8-minute focus to near point and far point, respectively. Reasonably, extreme focus had no corresponding effect on far point of focus.

There appears to be a logical connection between this and the mechanical limit of compressibility of the lens itself at the far point, as compared to the more flexible situation for near point, given the hypermyopic tendency of the lens capsule. Not inconsistently, Ebenholtz and Zonder argue that this supports the Gilmartin and Hogan (1985b) hypothesis that the normal role of sympathetic nervous system innervation is (of biological significance) to counteract accommodative hysteresis after prolonged near work. Huntergatherers would find it a good survival trait to be able to focus a distant threat rapidly after prolonged foraging or grooming near work.

Gilmartin and Hogan (1985a and b) established that the apparent effective range of focal length increase mediated by the sympathetic nervous system is no greater than about a quarter the parasympathetic's dynamic

Table 2. Samples of measured tonic focus.

Researcher(s)	Nominal Mean/ Equivalent Object Distance	Reported Std Dev	Number of Subjects
Otero (1951)	61.18/.85 m	data not given	3
Campbell (1954)	60.64 D/1.56 m	0.36 D est.	13
Leibowitz and Owens (1975)	61.7 D/0.59 m	0.72 D	124
Leibowitz and Owens (1978)	61.52 D/0.66 m	0.77 D	220
Simonelli (1979)	61.19 D/0.84 m	1.5 D	154 (recruits)
Simonelli (1979)	62.67 D/0.37 m	2.57 D	114 (students)
Gilmartin, Hogan, and Thompson (1984)	61.66 D/0.60 m	0.65 D	20
Barber (1989)	60.93 D/1.08 m	0.45 D	138 (military)

dioptric range. It should be kept in mind that small negative dioptric changes correspond to increasingly large physical distances, becoming very significant as baseline focus distance exceeds arm's length. What is of most interest from a psychological perspective, however, is that the mediation of both nervous system partitions increases the complex of pathways affecting accommodative behavior.

Hennessy (1976), summarizing findings in the literature and, more specifically, his work at Pennsylvania State University, highlights five major findings. **First**, there are a variety of circumstances, including low light, viewing an empty field, stress, and viewing through optical instruments, under which the eye will lapse toward tonic focus. **Second**, each individual has a characteristic resting focus. In the population, this seems to be a normally distributed variable. **Third**, individual tonic focus can predict functional myopia. In this context, Henessey seems to have been referring to degree of nocturnal myopic loss of acuity. **Fourth**, under conditions where *some* stimulus to accommodation is present, accommodative distance seems to be a "compromise" between object distance and tonic focus, with a concomitant diminution in acuity. **Fifth**, in the context of tonic focus, the degree of functional myopia is an individual experience, predicated on certain psychological and environmental factors. These factors, he reports, include elevated levels of physical or emotional stress, low focal demand of the central stimulus, and the presence of near objects in the peripheral visual field.

The Pupillary System

Pupil response, also energized through the action of the third cranial nerve, interacts with both convergence and, more apparently, visual accommodation as discussed earlier. Helmholtz (1867/1962) points out the direct, mechanically induced reduction in pupil size with constriction of the ciliary body effecting inward (increased) accommodation. The latency for this type of pupil response is similar to that of accommodation at around 0.32 sec. Pupil responses to changes in illumination are considerably faster, on the order of 0.24 sec. (Campbell and Westheimer, 1960).

Several investigators (Campbell, 1957; Tucker and Charman, 1975; Hennessy, Iida, Shiina, and Leibowitz, 1976) plotted accommodative range as a function of (artificial and natural) pupil size. Where the theoretical slope of 1.0 reflects perfect correspondence between actual dioptric target distance and dioptric accommodation distance, the slope of response functions for targets at various distances decrease steadily with pupil size. These functions roughly pivot about (i.e., converge to and diverge from) mean tonic focus and, generally, reflect best accommodative response under binocular viewing conditions with natural pupils. The corresponding response function has a slope of just over 0.7 for pupil diameter estimated at between 4 to 5 mm under binocular viewing conditions. The reported slope is about 0.6 for natural monocular viewing. Slopes diminish monotonically to a minimum of about 0.1 as artificial pupil diameter decreases to 0.5 mm. These effects prevail when ambient illumination is adjusted to hold retinal illuminance constant.

Depth of focus and corresponding depth of field are affected by pupil size in a very direct way. The size of blur circles caused by any accommodative error is exactly proportional to pupil diameter. Doubling pupil diameter, therefore, doubles the size of the blur circle and, given a fixed threshold of critical blur circle size, increases the need for more accurate focus reflected in the above findings. *Hyperfocal distance* may be described as the physical distance to the near edge of the depth of field, most often defined with reference to a lens focused to infinity. Hyperfocal distance, given the above findings, increases with increasing pupil diameter. See Marasco (1995) for a clear and concise treatment of hyperfocal distance, depth of field, and formulae relating this parameter to engineering imaging displays.

Retinal illuminance, i.e., the amount of light stimulating the retina, is generally a function of pupil size. Effective pupil size is mediated by certain directional restrictions imposed by the physical columnar arrangement of the receptors in the retina. Stiles and Crawford (1933) found that rays entering the eye through the center of the pupil stimulate retinal receptors (specifically cones) much more efficiently than rays entering through the edges of the pupil. This *Stiles-Crawford Effect* (see Figure 6) can be expressed as a ratio, R, adjusting the easily measured entrance pupil radius, r, in mm, such that:

$$R^{1/2} = \frac{2\sqrt{\dfrac{1-e^{(-0.105r^2)}}{0.105}}}{2r} = \frac{\textit{corrected}\text{ pupil diameter}}{\text{observed pupil diameter}} \quad (2)$$

R, the above squared, expresses the ratio based on pupil area. Retinal illuminance, I (expressed in trolands, cd/mm^2), can be estimated by the formula:

$$I = R \times (\pi r^2) \times \text{ Luminance} \quad (3)$$

where luminance is expressed in cd/m^2. Representative values are presented in Figure 7.

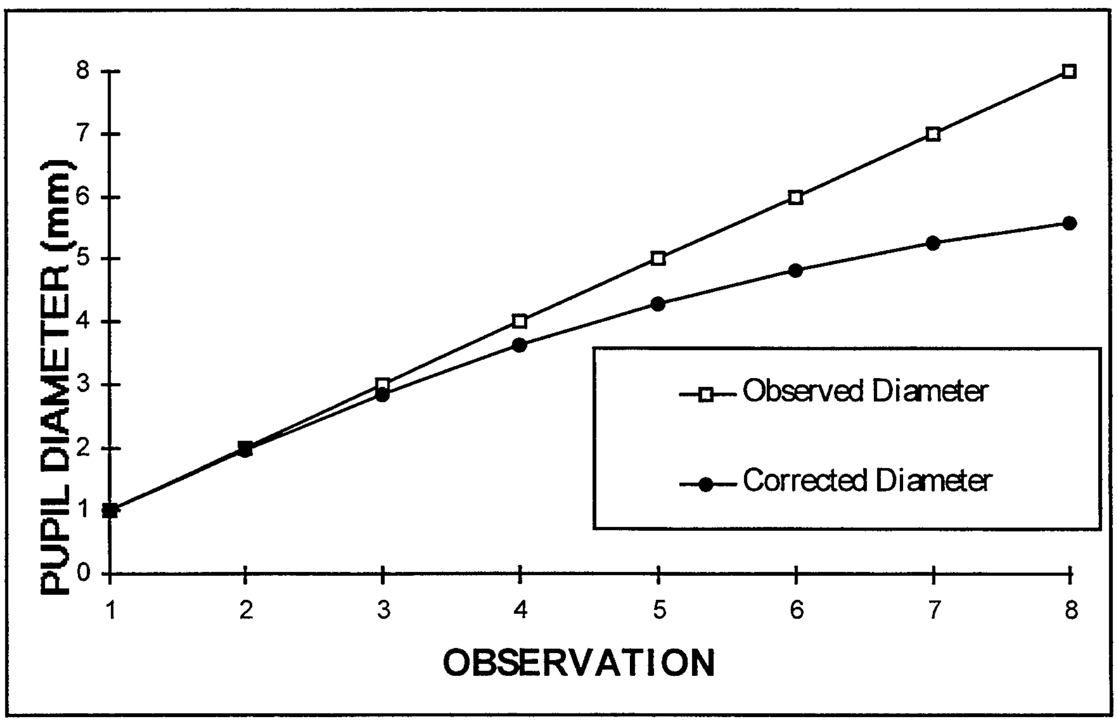

Figure 6. Stiles/Crawford pupil diameter correction (Campbell, 1957, p. 160).

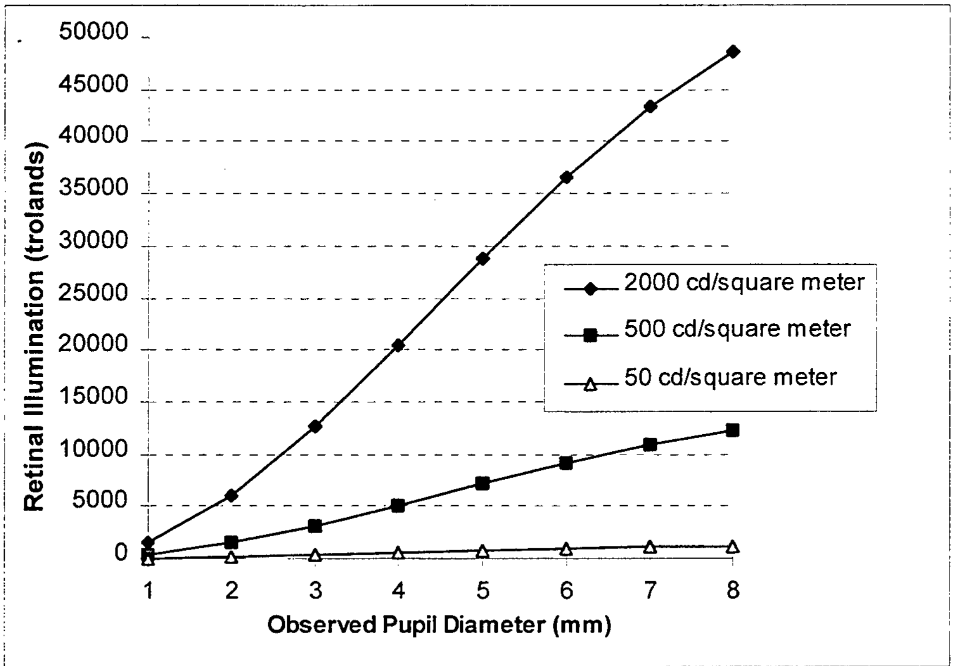

Figure 7. Retinal illumination as a function of ambient luminance and observed pupil size.

Riggs (1965) compiled data from a number of investigators to show that visual acuity is linearly related to artificial pupil diameter up to about 1 mm. Acuity is then optimum across the normal range of photopic pupil sizes (about 2 to 5 mm). Riggs accounted for this by speculating that the Stiles-Crawford Effect compensates for the distortions caused by the monotonically increasing spherical aberrations with larger pupil sizes.

The Ocular Vergence System

The visual array is integrated by the human visual system based on two separately registered subarrays, one from each eye. A great deal of psychophysical investigation has addressed the specific mechanisms of and critical influences on the reliably integrated world we perceive. According to Arditi (1986) , "Disparate images are said to fuse into a single percept localized in depth (and are) widely considered as two aspects of the single hypothetical process called *fusion*."

Our eyes are separated by a horizontal interpupillary distance (IPD) of between approximately 5.1 cm (5th percentile, civilian females, Salvendy, 1987) and 7.2 cm (99th percentile, military males, VanCott and Kinkade, 1972). Figure 8 illustrates the relationship between interpupillary distance, object distance on the frontal central axis, and angular convergence. *Ocular vergence* coordinates the point of fixation and the fusion of the resulting visual array through the combined action of the third, fourth, and fifth cranial nerves.

As early as 1833, Professor Wheatstone (1852) had demonstrated that when convergence was manipulated by artificial means, while care was taken to retain a constant visual angle, the apparent size of an object "may be made to vary with every alteration of the angular inclination of the optic axes (p. 505)."

Stark (1983) discusses, in control theory terms, the important *triadic synkineses* between accommodation, the pupil mechanism, and ocular vergence. These are, he states, characterized by coupled lower-level motor movements (i.e., synkineses) that are difficult to modify. The zone of clear binocular vision is a range within which the dead space of accommodation, made larger by pupillary constriction, enables the triadic system to handle noncongruent stimuli. At the edge of this zone, the sensory-visual and oculomotor mechanisms can "choose" either to accept blur and maintain vergence or to accept disparity and adjust accommodation.

Maddox (1893, p. 106) describes four, generally temporal-sequential, **elements** of convergence. These are: tonic, accommodative, fusional, and voluntary, with its hybrid, convergence due to "knowledge of nearness." The *tonic* element of convergence moves the eyes from a resting state (tonic vergence) to place the object of fixation on at least one fovea. This fixation reflex will initiate an appropriate *accommodative response* and trigger vernier, "added" movements, *fusion convergence*, to achieve bifoveal fixation. In the case of near object fixation, *accommodative convergence* is "added" before any fusion convergence is applied, if needed.

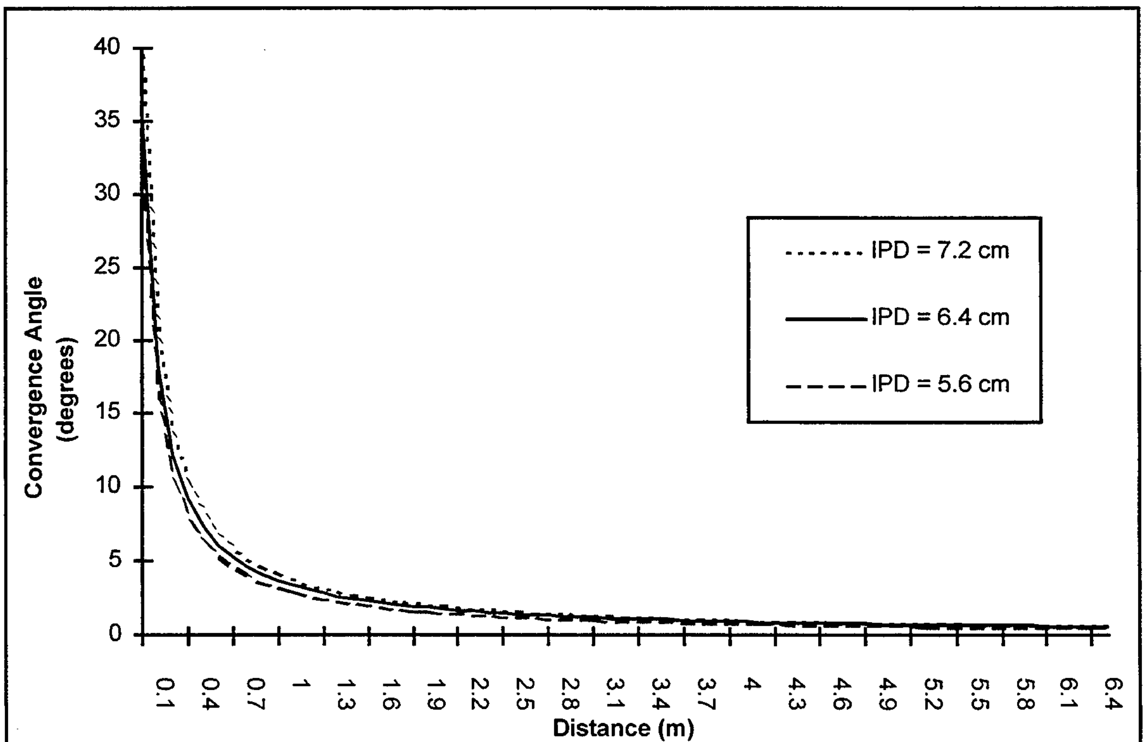

Figure 8. Angle of convergence by object plane distance.

Owens and Leibowitz (1983) describe the basic characteristics of tonic vergence as distinct from the tonic vergence ***elements*** described above. In death or deep sleep or anesthesia, the eyes depart from tonic vergence to their uninnervated mechanical/anatomical suspensory state of extreme divergence. Further evidence indicates that differences in lateral heterophoria, fixation disparity, and distance perception are related to individual differences in tonic vergence. They estimate an average dark convergence (unstimulated, therefore, non-fusional) at a distance of about 120 cm (less than 3.5-deg. convergence). This is comparable to Westheimer's (1963) estimation of an "intermediate position" between 60 and 100 cm (less than 7-deg. convergence).

Fincham (1962) found that dark convergence and dark focus did not correspond in position or variability within subjects. Individuals presented wide individual differences in dark convergence (0.53 m to slight divergence) with an overall average of 1.37 m. When both tonic accommodation (TA) and tonic vergence (TV) were measured simultaneously with and without Timinol intervention by Gilmartin et al. (1984), the 0.85 D myopic shift in TA was not associated with a systematic shift in TV ($r = 0.09$, p = n.s., n = 10).

Degradation across a wide variety of stimulus conditions follows a pattern of over convergence to distant stimuli and under convergence to near stimuli. *Panum's area* is defined by the amount of retinal disparity between images of an object that can exist while a person still perceives an object as single (i.e., without suffering diplopia). Retinal eccentricity has an expanding effect on Panum's area, monotonically increasing from as little as 6 min. of arc at zero deg. eccentricity to as much as 40 min. of arc at 15 deg. eccentricity. This correspondingly greater fusional tolerance to retinal disparity reduces the accuracy of vergence response, facilitating a regression toward the individual's intermediate value. Tonic vergence is much more sensitive than accommodation to hypoxia or drugs like amphetamines and alcohol, which affect the efficiency of central processes.

Further, the tonic vergence of an individual is "plastic," subject to modification through manipulation of binocular parallax and fixation distance. In a classic perceptual adaptation paradigm, Owens and Leibowitz (1980) used base-out prisms and -1.25 D lenses to "adapt" three groups of subjects, each exposed to a different level of perceptual-motor activity. As predicted, dark vergence adapted (shifted) considerably. This shift was least for the low activity group. Dark focus was unaffected in all groups. For distance perception measurement, subjects were asked to point to a light source in a low illumination setting presented over a range of relatively near distances (< 1m). High and moderate activity groups demonstrated large changes in perceived distance between preadaptation and postadaptation. The low activity individuals showed little change. The investigators did not measure accommodation, however, while distance judgments were made.

There had been a long-standing controversy concerning the specific mechanism of tonic vergence. The controversy concerned whether it involved active-convergence/passive-divergence, as classically held, versus active, counter-balanced vergence in both directions. The issue was conclusively resolved when it was demonstrated through electromyography in favor of bi-directionally active vergence (Bjork, 1952; Adler, 1953).

Adamson and Fincham (1939) affirmed the clinical fact of human intolerance to binocular parallax (but only) when it results in diplopia, "double vision." Their study systematically altered ocular vergence angles from exophoric through orthophoric to esophoric with a modified haploscope while independently measuring accommodative tolerance to lens-induced refraction (in their terms, "light vergence") changes. They found that accommodation (within the reported dead zone) lagged vergence changes over a considerable range, for example, when divergence was induced for targets at 1/2 m or when convergence to 1 m was induced for targets at infinity.

Accommodation consistently increased slightly from normal with excess convergence and decreased slightly with excess divergence. When clear vision finally broke down due to manipulations of vergence "convergence dragged accommodation along with it." This contrasts with the finding that lens-induced light refraction changes did not immediately result in changes in (lagging) accommodation. Only when significant blurring occurred due to refractive error did large changes in accommodation take place. When large changes in accommodation were induced by even larger refractive manipulations, accommodative changes could induce changes in phoria large enough to cause diplopia, quickly eliminated by compensatory vergence change.

Using their data, calculated Pearson *r*'s of 0.85 and 0.81 reflect the reasonably strong relationship between accommodation and convergence when one or the other was directly manipulated under binocular conditions. These high correlations reduce to 0.25 and -0.07, respectively, under monocular conditions, generally characterized by accommodation tending more toward the normal object distance. This would seem to suggest that "normal response linkages" between both systems depend on binocular viewing. Of interest, under monocular conditions subjects with naturally divergent phorias (exophorias) tended to under accommodate relative to their binocular response. Consistently, subjects with naturally convergent phorias (esophorias) tended to over accommodate relative to binocular viewing.

From their replotted data, shown in Figure 9, it would seem that convergence manipulations had systematic but small effects on accommodation (beyond the dead zone amplitude). Under binocular conditions, exophoric manipulations of vergence caused accommodation to exceed limen values with as much as 12.25-deg. "divergence" beyond target. Their subjects seemed more sensitive to esophoric manipulations,

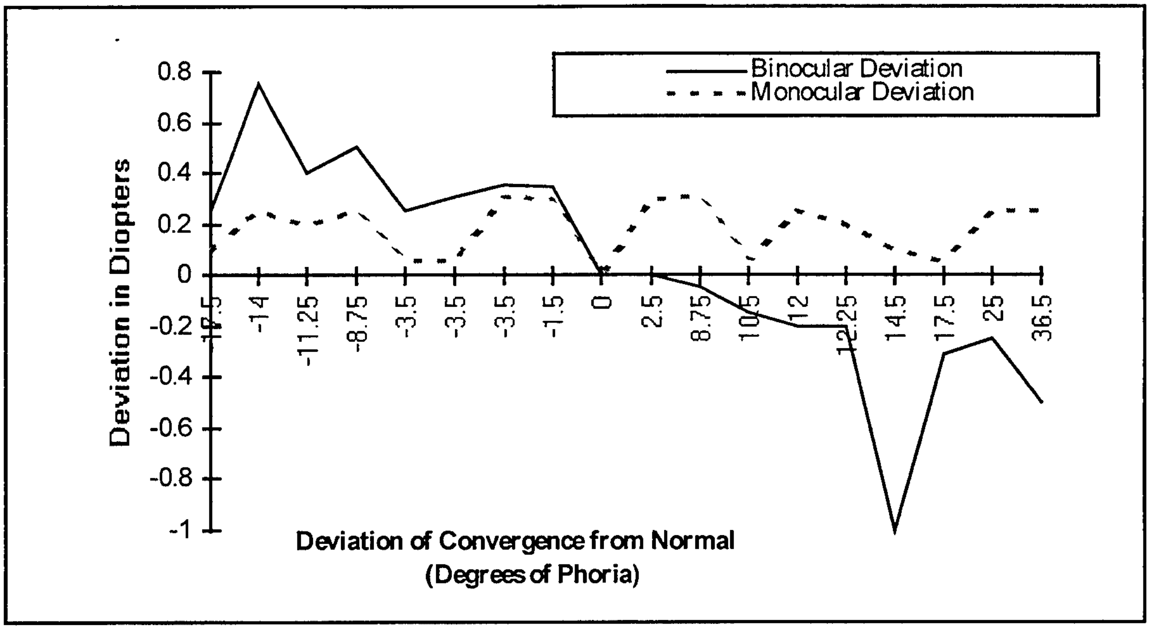

Figure 9. Manipulated ocular vergence effects on accommodation based on Adamson and Fincham (1939), Table IV.

consistently exceeding the dead zone threshold in dioptric shift somewhere between 3.5 and 8.75 deg. of excess convergence.

Owens and Leibowitz (1983), based on an extensive review of available evidence, concluded that tonic or dark vergence and tonic accommodation were only weakly related; that perceived (near) distance is related to dark vergence and not to tonic accommodation; and that dark vergence may, in fact, be independent of tonic accommodation.

Stereopsis is defined as visual perception of depth or three dimensionality, commonly referring to depth perception based on lateral retinal disparity. Stereopsis has become a major area for investigation of visual perception of space. A conceptually important subset of the stimulus-response relationships that must be resolved within the framework of stereopsis are the *horopters*. A horizontal or a vertical horopter is a plot of points with no apparent retinal disparity when an object is fixated frontally at a set distance. The shape of the horopter is dependent on the fixation target distance.

In one method of detailing an empirical horopter, subjects are asked to fixate on a frontally presented target and adjust a more eccentrically presented target onto the same fronto-parallel plane. Empirical plots of horizontal horopter data present a family of curves, nearly flat (fronto-parallel) at about 6 m, increasing in concavity (bending inward) as the target distance decreases. Beyond about 6 m the curves reverse direction, but are much less dramatically deviant, convexing only slightly. An illustration of these general trends is offered at Figure 10. The much less studied vertical horopter results in a family of straight lines originating nearer the observer's feet directly below the eyes, passing through the point of fixation. Again directly dependent on distance, the vertical horopter tilts away from vertical with increasing distance from the observer.

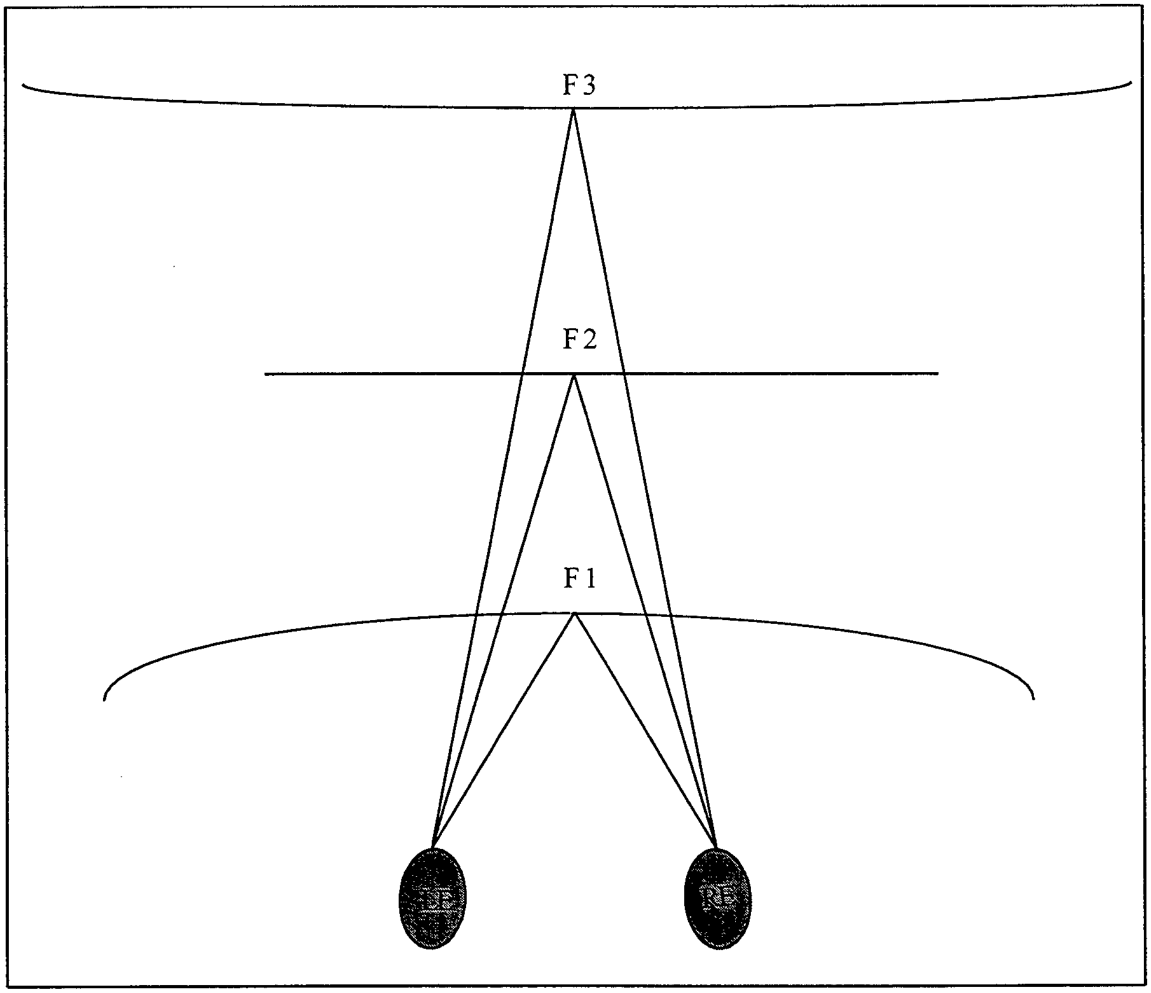

Figure 10. Generalized empirical horizontal horopters. Judged fronto-parallel curves illustrate patterns of fused images of peripherally displaced rods as subject fixates F1 versus F2 versus F3.

Newsome (1972), using similar methodology, measured apparent size of a centrally, monocularly fixated target at 1 m by adjustment of the distance of peripherally presented comparators. With increasing eccentricity, comparators had to be moved closer, resulting in enlargement at a rate of approximately 1 deg. of visual angle for every 12 to 15 deg. of eccentricity. Changing light conditions from mesopic to scotopic with appropriate stimulus adjustments had no effect on the results. Increasing the target distance to 100 m (with a slight decrease in target visual angle from about 4.25 deg. to 3.35 deg.), resulted in completely analogous effects, diminishing to a rate of 1 deg. of visual angle enlargement for each 20 or so deg. of eccentricity.

The *AC/A ratio*, a widely documented and individually stable metric (Alpern, Kincaid, and Lubeck, 1959), relates ocular Accommodative

Convergence in prism diopters (Δ) to Accommodation (in D) at a variety of object distances over which vergence and accommodation are linearly related. This is generally the same range over which stimulus distance and accommodation are found to be linearly related. Where d_{verg} is the distance of actual convergence in m, and IPD is interpupillary distance in cm:

$$\text{Prism Diopters } (\Delta) = \text{IPD}/d_{verg} \tag{4}$$

While there are wide individual differences, the ratio is generally between 3 and 5 in the general population. Most individuals with normal vision have AC/A (based on the above formula, Δ/D) ratios a little over half of their IPD, with an average 1.76:1 ratio of convergence to accommodation change. This translates to significant exophoria (error diverging from correct, stimulus-based) relative to targets at reading distances. Alpern et al. caution that a distinction should be made between a *response AC/A* ratio, where actual accommodation is measured, and a *stimulus AC/A* where accommodation is assumed based on stimulus conditions (so that: $d_{acc} = d$). They indicate that a "typical" response AC/A ratio can be estimated by multiplying the corresponding stimulus AC/A ratio by 1.08.

As measured clinically at standard near distances, the AC/A ratio is remarkably constant, with or without refractive correction, and is unaffected by age. Owens and Leibowitz (1983) have speculated that any interpretation of the true relationship between vergence and accommodative response should take into account differences in AC/A ratios, especially in relation to *perceptions of near distance* under low light (scotopic) conditions. At short distances under reduced, dark conditions, using a point light source as a stimulus, Owens and Leibowitz (1976) demonstrated that phoria-adjusted and normalized convergence measures correlated well ($r = 0.76$) with perceived distance out to about 4 m.

Binocular vision has been demonstrated repeatedly to improve visual performance on average over monocular vision, suggesting both integration and optimization functions at work. For example, Legge and Ruben (1981) found that binocular contrast-sensitivity was greater than the average of the sensitivities in the right and left eyes but less than the sensitivity in the higher sensitivity eye. Binocular contrast sensitivity is apparently determined more strongly, but not entirely, by the greater of the monocular sensitivities. Levelt (1968) found that a similar condition obtains for unequal luminances; perceived brightness is biased to the brighter eye. Consistently, in a phenomenon known as Fechner's paradox, when the lower-luminance eye is occluded, the perceived brightness exceeds that reported with both eyes open. Legge and Ruben (1981) report a contrast-based version of the paradox, finding that binocular matching functions for compared sine-wave stimuli behaved as if the eye receiving the highest contrast disproportionately dominated perception.

Campbell (1960) simultaneously recorded accommodation of both eyes while subjects fixated a target at 0.5 m (2 D demand). He found extremely high correspondence (in phase and amplitude) in the tremor-like oscillations mainly between 0.5 and 2.0 Hz associated with this accommodation task. He noted that in other investigations (e.g., Campbell et al., 1959) involving monocular measurement, the sparser the distance cues, the greater the power of the lower frequency oscillation components with a corresponding reduction in high frequency components. He argued that this high correlation indicated that central innervation (at or above the point where the two third cranial nerves are functionally conjoint) is implicated. He further noted that the relative magnitude of the oscillations in this study compared favorably to those obtained in monocular studies where binocular convergence was not fixed, targeted, or controlled (conceivably damping oscillatory effects). He concluded that this made it unlikely that the known linkage between convergence and accommodation had any independent or more peripheral effect.

The Retinal System

In a nominally representative optical system, for any given object distance, there is a single precise lens power that will create a focused real image (inverted) at an image surface. The specific image surface of interest in the human visual system is the retina covering the posterior two thirds of the eye's interior.

The retina is composed of photoreceptors, an elaborate network of neural tissue, and blood vessels. Light passes through the lens system, converging rays to form a real image for projection at or near the surface of the retina. Light must then pass through variable depths (least at the fovea) of minor blood vessels (retinal capillaries) and neural tissue to reach the tightly packed posterior bodies of photo receptors. Only then are these receptors stimulated by the direct light rays and by the long wavelength light reflected from the pigment epithelium and choroid coat that make up the last layers inside the sclera, the tough outside coating of the eye.

Rods, numbering approximately 120 million, are relatively large high-sensitivity receptors responsible for low light (scotopic) vision. The scotopic range corresponds to light intensities below about 1/1000 cd/m^2 to the lower threshold corresponding to starlight vision. Rods are fairly evenly distributed across the retina, though virtually absent in the central .15 mm and ineffective in the central 0.3 mm (at least 1 deg.) of the retina, corresponding to the central fifth of the fovea, the center of which defines the origin of the visual axis (see Livingstone and Hubel, 1987).

In contrast, cones, numbering approximately seven million, are most highly concentrated in the central fovea, supporting the central few degrees of the visual field in an extremely leptokurtic distribution. Cones in the majority of humans have one of three different pigments giving them three different color sensitivities. As mentioned earlier, blue-sensitive cones are absent at the very center (the central fixation area, about 8 min. wide) of the fovea, but are well represented elsewhere (Wald, 1967). Cones are sensitive to color and fine detail under higher (photopic and mesopic) illumination conditions. The photopic range includes light intensities from about 100 cd/m^2 (about 2 footlamberts) to damagingly bright levels (welding flash or sun's surface, over 300,000 cd/m^2). Photopic vision is limited to "cone only vision."

The mesopic range is defined from a rod-saturation point at about 100 cd/m^2 (a little brighter than white paper lit by a standard candle at 1 ft.) to the upper bound of the scotopic range. While rods and cones complement each other in this range, their individual efficiencies are markedly depressed.

All cone sensitivity ends at the top of the scotopic range, at about 0.0011 cd/m^2 (white paper in clouded moonlight, about 0.0008 footlamberts). Rods (conditional on about an hour of dark adaptation) continue their impressive sensitivity to photonic energy to an absolute threshold of about 0.0000032 cd/m^2. Rods and cones transduce electromagnetic radiation into neural impulses through photochemical processes mediated by their respective rhodopsin families of pigments.

Toates (1972), in his classic tutorial, points out that the most central region of foveal cones (corresponding to about 30 min. of visual angle) have been strongly implicated as primary agents in the accommodative reflex under photopic and, less effectively, mesopic conditions (Campbell, 1954; Crane, 1966; Fincham, 1953a; Wald, 1967). Fincham (1951, p.391), researching the accommodative reflex, noted that:

> ...no accommodation reflex to changes in the vergence of the light takes place while fixation is held...and...to produce the reflex it is necessary for the eye to scan so that the image travels across a certain area (the central fovea where the Stiles-Crawford effect could mediate blur gradient detection) of the retina. ...such observations as have been made indicate that a rotation of 6 min. may be sufficient.

In a series of experiments specifically investigating instrument myopia, Hennessy (1975) reports results that indicate that objects in the near-periphery can stimulate accommodation. *Instrument myopia* is a sustained state of over accommodation during observation through an optical instrument (telescope, microscope, etc.). He manipulated textured and untextured annuli surrounding a centrally presented target cross. Each annulus presented a near periphery at 5 deg. or 8 deg. and an outer edge at 11.9 deg. Both target and surround distance were varied.

An untextured (plain, flat black) annulus had no effect on accommodation distance. A textured annulus (high-contrast, checkerboard grid pattern, 51.5

min. per side) systematically biased refractive state as a function of surround distance (from 3.0 D to 0.0 D) on the order of 0.6 D (or, at a rate of about 0.2 D/D). Hennessy concluded that this was important but that it did not explain the much larger (roughly 2.0 to 3.0 D) instrument myopic effect. He concluded that the overall instrument myopic effect was much more completely and parsimoniously explained by a regression to tonic focus.

Ciuffreda (1991) meta-analysed the data from six major studies to define a response gain profile as a function of retinal eccentricity. His presentation would indicate a steep drop in gain to about 25 percent at a 10-deg. eccentricity, flattening slowly to negligible gain beyond 15 deg.

Photon absorption at the molecular level triggers a cascade of processes that result in a hyperpolarizing receptor potential (Bruce and Green, 1992). Through a logarithmic coding of light intensity by impulse frequency, photoreceptors are the primary agents in light adaptation. **Acuity** (ability of the visual system to resolve fine detail) is largely a function of the density of photoreceptor packing. Foveal cones in humans are physically separated by at least 20 arc sec. Falcons, typically able to resolve to 12-sec. separation versus 30 for human observers, have evolved a density packing three times the human norm (about a 7-sec. separation). This density is traded off against the cross-section of the individual cells that dictates the probability of achieving photonic response threshold, the cell's sensitivity. The smaller profile and size of cones versus rods reflect their respective dominant characteristics.

Enoch (1973) and Blank and Enoch (1973) report a phenomenon, defined here as part of the accommodative system function, associated with very near accommodation. Constriction of the ciliary muscle during accommodation, in addition to efferent/afferent neural activity and lens effects, causes the leading edge of the retina to advance. The choroid, the layer that carries major blood vessels to and from the retina, is attached to the retina throughout its surface and is continuous, at its anterior limit, with the meridional fibers of the ciliary muscle. The investigators measured an increase in the surface area of the retina of 2.4 percent (at 10 D, or 70 D nominal) and asymmetry in the temporal versus nasal stretch due to the asymmetric position of the optic nerve head. Some logical implications of this are interesting and worth exploring.

In conjunction with greater object distance, increased distance of accommodation, and increased information compression in the visual array, a ciliary-mediated retinal "un-stretch" might marginally increase effective photoreceptor density. This would then result in a compensatory increase in resolution, lagging, of course, the loss in resolution due to distance. This phenomenon should be complementary to accommodative effects on retinal image size and, therefore, imply that farther accommodation increases not only the area of retinal stimulation per unit angle of stimulation but also the density of photoreceptors available to process the retinal image. Since the specific gradient of expansion and compression is unknown (making this entire discussion highly speculative), a simple additive relationship based on the already estimated magnification for any given level of accommodation was applied in Table 1 to estimate cone stimulation for the nominal eye.

While the threshold for acuity is typically associated with two-line discrimination at about 30-sec. of visual angle, humans are capable of much finer vernier or pattern discriminations. This *hyperacuity*, as termed by Westheimer (1975), is reflected in, for example, vernier colinearity judgment thresholds as low as 5 to 0.5-sec angle. Logically 4 to 40 times the resolution based on density packing of foveal cones, this phenomenon points to higher order processing and data integration (see Watt and Campbell, 1985, for a research/theoretic exemplar). This data-integration is analogous to a maximum level of "image enhancement," effective for an extremely limited number of features and feature conditions. Westheimer himself speculated that unraveling the mechanisms underlying hyperacuity might aid in the understanding of how perceptual systems effectively adapt to offset the degradations of age and illness. Morgan (1986), in the context of his work investigating interactions between contrast and spatial contiguity, discusses the methodological and inferential importance of hyperacuity studies in deciphering higher cortical processing mechanisms.

The functional specializations and data reduction processes begun at the photoreceptors are compounded in the organization of the four nerve types composing the neural layer. The *horizontal cells* effect lateral communication among stimulated photoreceptors. *Bipolar cells* process and transmit multiple photoreceptor impulses to the primary ganglion cells. *Amacrine cells* mediate selected lateral transmission at the level of the bipolar cells. *Ganglion cells* form the neural pathway that is called the optic nerve.

The foveal cones (occupying less than 0.3 percent of the total retinal area) are augmented by the highest concentration of bipolar, horizontal and amacrine connections. This effectively gives foveal cones more or less direct (one to one) representation at the ganglionic layer and maximizes mutual effects of proximal cones. The ganglion cell bundle, composed of approximately one million long axons, constitutes the optic nerve, the second cranial nerve. The optic nerve departs each eye on the nasal side and slightly below the primary orthogonal planes of the optic axis; the resulting blind spot or optic disk is about 2.5 mm in diameter.

In optical systems, color discrimination is made possible by the presence of at least two differentiated wavelength sensors. In human vision, three classes of cones may be differentiated by the wavelengths to which they are maximally sensitive. These classes of cones are roughly the blue/violet (419 nm, called blue sensitive cones, absent in the central 7-min. field of the fovea), yellowish-green (531 nm, called green sensitive cones), and greenish-yellow (558 nm, called red sensitive cones). Cones, as a group, are maximally sensitive at a wavelength of about 555 nm and are individually less sensitive to photonic stimulation than are the rods. Rods have a peak wavelength sensitivity at approximately 500 nm but, under photopic conditions, are saturated beyond usefulness. Under scotopic conditions, color differentiation in the monochromatic rod sensitive domain is not possible. Under mesopic light conditions, both cone and rod luminous efficiencies are degraded.

In addition to these distinctions, retinal photoreceptors exhibit temporal sensitivity to patterns of light intensity through the processes of rapid *light adaptation* and gradual *dark adaptation.* Light adaptation responds with a high neural impulse rate to a sudden increase in light intensity, stabilizing to a lower, constant firing rate as ambient light conditions stabilize. Conversely, dark adaptation involves a gradual adjustment in photoreceptor sensitivity to ambient light conditions. Light adaptation responses are relative to the current state of dark adaptation (Bruce and Green, 1992).

Extraction of information about the pattern of light impinging on the retina continues in a series of transformations of spatial, temporal, and wavelength parameters. Ganglion cells have been demonstrated to exhibit lateral inhibition, selective inhibition of adjacent cell responses given local stimulation. In vertebrates, a common pattern of ganglion cell response is roughly concentric with a center and surround. Investigators have confirmed both a "center-on" response to center stimulation and a "center-off" response pattern to the removal of center stimulation.

Additionally, two general classes of ganglion cells demonstrate concentric receptive fields sensitive to patterns of light intensities in distinctively different ways. *X* ganglion cells respond linearly to differences in light intensities in sine-wave gratings falling on adjacent areas and sustained responses to stationary gratings. *Y* ganglion cells, however, respond at a baseline level only to the presence of a *moving* sine-wave grating with the pattern of contrast change superimposed in the changing amplitude of response. Center surround fields are larger for *Y* cells than *X* cells, while fields of both types increase in diameter with increasing distance from the fovea. *X* cells are more heavily represented near the fovea, *Y* cells more heavily in the periphery.

In addition to the concentric, X and Y style, response field organizations, others have been identified. At least four varieties of slower responding *W* ganglion cells seem to provide "on-off" and edge detection sensitivity to moving stimulation (relative to the field) or direction selectivity, responding most strongly in one and not at all in the opposite direction.

Both *X* and *W* ganglion cells, with slow-conducting axons relative to Y type cells, have been demonstrated to specialize in the transformation of color information by means of what Bruce and Green (1992) call ***opponent-color*** responses. The opposition comes in the form of an increased firing rate for one color and an inhibited firing rate for the opponent. Identified opponent pairs are **+Blue-Yellow**, **+Red-Green**, **+Yellow-Blue**, and **+Green-Red**. Intensity information is reliably transmitted at the boundary between these divergent responses.

Together, the above contribute to a fairly clear and predictive model of the processes translating the raw, optical retinal image into neural signals departing the eye. It is incomplete, however, at least in that it offers no explanation for the fact that certain distal stimulations affect firing rates of retinal ganglion cells as far as 90 deg. removed, well outside of the concentric fields described.

Pathways and High Level Projections

Neurophysiologists have traced the maintenance of orderly topographical relationships between retinal photoreceptors and higher pathways and projection areas. At the most general level of such relationships, within each eye, contralateral portions of the visual array are projected as inverted real images onto corresponding retinal surfaces. The resulting transformed signals maintain orderly arrangements as they depart the eye in the ganglion cell bundle. The two optic nerves converge and systematically merge at the *optic chiasm* to diverge again as binocular information concerning "left" versus "right" visual array segments to their bilaterally symmetrical, opposite (hemispheric) higher pathways for continued processing.

In mammals, one of two main pathways projects some Y and most W cells to the superior colliculi, midbrain structures homologous to the optic tectum in lower vertebrates. This pathway is referred to as the *retinotectal path,* implicated in a phenomenon referred to as blind vision. Diamond, Scheibel, and Elson (1985) describe the superior colliculi as reflex centers influencing the position of eyes and head in response to visual, auditory, and somatic stimuli. A feedback path (corticotectal) also connects the visual cortex to the superior colliculi. Other minor pathways, about which little is known but more is rapidly being discovered, project some W cells to the hypothalamus, tegmentum, and the ventral lateral geniculate nuclei (LGN) structures. Together, these paths are speculated to provide diurnal cycle regulation, postural and body motion processing mediating short loop feedback to the oculomotor systems, peripheral visual field motion awareness, and control of the iris and lens.

The other main pathway projects impulses from X cells, most of the Y cells and a few W cells to synapses in the dorsal part of the two LGN of the thalamus. According to Diamond et al. (1985), the thalamus is currently thought to be the level of the central nervous system where sensations are first consciously experienced. Six layers, retinotopically mapped laminae, define the organization within each LGN. *Columnar registration* has been demonstrated in these six layers. Vertically corresponding cells in each layer have receptive fields registered to the **same** point in the visual array.

Three of the layers carry information from the contralateral eye's nasally projected retinal hemisphere, three the ipsilateral eye's temporal projection. As with all projections after the optic chiasm, cortical projections are of the binocularly originated, contralateral half of the visual field corresponding to the inverted real image at the retina. These cells demonstrate concentric receptive fields similar and roughly corresponding to their connecting ganglion cells.

Four laminae of the six in the previous paragraph constitute the *parvocellular stream* (smaller diameter and more numerous constituent cells), apparently responsible for conveying color and detail information (generally, an X cell correspondence). Two laminae making up the *magnocellular stream* (larger diameter individual cell) seem to specialize in general form and movement information (Y and W cell correspondence). Axons from the LGN form the optic radiations that project to the occipital lobe of the cerebral cortex. Interestingly, the existence of feedback paths from the cortex to the LGN suggests that the two LGN function in more complex roles than simple relays. This overall main pathway is called the *geniculostriate path.*

Examining findings of relevance nearer the beginning of the perceptual event chain, Phillips (1974) used a haploscope-optometer to measure static accommodative responses as a function of target spatial frequency and contrast. He found spatial frequencies less than 1 cycle/deg. and greater than 25 cycles/deg. resulted in (sine-wave) contrast gradients too shallow or steep, respectively, to drive blur-driven accommodation.

He further found that the **contrast** of a sine-wave grating at the threshold for detection of a given spatial frequency had to be increased 10-fold to elicit an accurate accommodative response. Closing the loop to present discussions, Livingstone and Hubel (1987) report that the sensitivity of magnocellular neurons to luminance contrast is 10 times higher (LGN-measured contrast gain, linear slope of response versus contrast) than that of parvo neurons. Consistent with earlier discussions regarding central foveal involvement, the magno system may support detection, but the slower, less transient and higher resolution parvo involvement is essential to accurate accommodation.

Carlson (1994) reports that retinal mapping continues in the striate cortex, but in a predictably distorted fashion. Approximately 25 percent of the cortical visual projection area is apparently devoted to signals originating at the foveal area (recalled to represent less than 0.3 percent of the retinal surface). A suggested **Archimedean** implication is that relatively small changes in foveal stimulation can evoke "**lever**aged" responses at the level of higher pathway activations.

Carlson further reports findings of investigators supporting increasing specialization, parallel processing and integrational implications. Beginning with the revolutionary findings of Hubel and Wiesel (1977) regarding selective feature sensitivity in the visual cortex, researchers have studied selectivity to orientation and movement, spatial frequency, texture, retinal disparity, and color. Table 3 provides a sampling of this rapidly unfolding set of psychologically relevant, physiological findings.

Table 3. Feature sensitivities, visual cortical cell types, and organization/response characteristics. (Freely adapted from Bruce and Green, 1992).

Feature Sensitivities	Cell Type	Organization/Response Characteristics
Specific *orientation* and *polarity* of contrast (i.e., black on white versus white on black)	Simple	Central sensitive receptive field; inhibitory to location and different orientation
Specific *orientation* and *movement*	Complex	Firing relative movement in specific orientation
Specific *spatial frequency*: Low frequencies for objects and form (magno-cellular system); high frequencies for edges and detail (parvocellular system)	Simple and some Complex	Multiple inhibitory and excitatory regions surrounding center. Receptive fields large enough to include 1.5 to 3.5 cycles of gratings
Specific *texture or periodic patterns*	Complex Texture	Sensitivity to deviations in both spatial frequency and orientation. High numbers of neurons to support perception of surfaces
Retinal disparity and *fusion* (for detailed discussions of theoretical evolution and relevant physiology see Tyler in Schor and Ciuffreda, 1983)	Four subtypes: Binocular corresponding; Binocular disparate; Monocular right eye; Monocular left eye	Stereoptic sensitivity to discrepancies in retinal location. Resolution of depth to about 12 sec. of arc
Color Retinal Disparity	Specialized Color-sensitive	Parvocellular organization into "blobs" distinctively exclusive of other features and specific to one or other eye

Perception, as the ideational process of scene and object interpretation, takes place beyond the striate cortex in the visual association cortex where, Carlson (1994) has concluded, two physiologically and functionally distinctive paths and streams of analysis take place. A downward (ventral) extrastriate path ends in the inferior temporal lobe. Its function is apparently the analysis of **what** an object is. This ventral stream appears to receive information equally from the magno- and parvocellular systems. The other, upward (dorsal) path terminates in the cortex of the posterior parietal lobe and apparently deals with **where** objects are located. The dorsal system depends mostly, but not exclusively, on magnocellular input with its lower resolution (and associated acuity) but greater sensitivity to contrast and movement.

Within these terminal zones for visual information processing, the retinal map is roughly duplicated in each of dozens of regions of feature specialization. These regions are apparently organized hierarchically with a primarily upward processing path and only limited downward information flow. Evidence from primate selective lesion studies supports a view that near the top of this hierarchical arrangement are cells with receptive field projections covering large segments of the visual field. Significantly, some of these cells actually seem to be specialized to respond to specific **objects** or object class arrays rather than discrete feature primitives.

In another interesting line of investigation, Johnston (1986) related cortical mapping to Gibson's (1950) spatial density gradient and its linkage to the direct perception of distance and relative size in space. He models the inverse magnification functions that describe retinal-cortical mapping relationships. For example, at 0.1 deg. of eccentricity from the fovea, the corresponding inverse magnification at the cortex across a variety of primate studies is about 0.2 deg. per mm. At 1.0 deg. of eccentricity there is little change to about 0.25 degrees per mm. At 10 deg., however, inverse magnification is down to 1 deg. per mm. His modeling procedure is based on a planar/polar projection of a striate cortical map. The resulting projection, when viewed through its polar axis, corresponding theoretically to the visual axis, presents a compelling correspondence to the horizontal surface gradient in real space. Johnston (1986, pp. 329-30) argues that:

> The cortical map is not a restatement of the retinal image or a "distortion" but a spatial transformation which constitutes a stage in visual information processing. The retina, though locally flat, is a globally three-dimensional, variable resolution, panoramic receptive surface. Retinal space is stretched at the cortex to emphasi[z]e the lateral projection of the visual field, offering a fundamental relationship between neural surfaces and the layout of surfaces in a three-dimensional environment.

TRADITIONAL PSYCHOLOGICAL CONSIDERATIONS

The Size-Distance Invariance Hypothesis and Related "Laws"

Visual angle relates the size of an object to its distance from the observer. An object of constant size will subtend a systematically larger visual angle the closer the object is to the viewer. During the birthing days of our modern science of psychology, Professor Wheatstone (1852), an eminent physicist, reported the "prevalent opinion" that convergence ("...inclination of the optic axes...") provided an immediately available percept of distance. This conscious percept then was seen to support a judgment about object size when combined with the physical magnitude of the retinal image.

Wheatstone had observed that, under normal conditions of vision, changing object distances caused several "circumstances" to vary simultaneously. For an approaching object retinal image size increased, inclination of the optic axes increased (convergence to maintain fusion), divergence of light rays from each point of the object increased (increasing the accommodation required for exact focus), and the dissimilarity of the pictures projected on the two retinae became greater. Wheatstone, on the basis of at least twenty years of relevant research, challenged the prevalent view. He proposed instead the following (p. 508):

> ...it rather appears to me that what the sensation, which is connected with the convergence of the axes immediately suggests, is a correction of the retinal magnitude to make it agree with the real magnitude of the object; and that *distance, instead of being a simple perception, is a judgement,* arising from a comparison of the retinal and perceived magnitudes. However this may be, unless other signs accompany this sensation, the notion of distance we thence derive is uncertain and obscure, whereas the perception of the change of magnitude it occasions is obvious and unmistakable.

Wheatstone, who perfected the stereoscope for his investigations, observed that manipulating convergence while holding real distance and object size constant, systematically changed perceived object size. He discussed the linkage between vergence of the optical axes and accommodation, noting that at extreme convergence, maintaining clear focus could be very difficult. He also reported that, having developed the necessary skill, he could maintain sufficient focus to clearly perceive changing object sizes with changes in convergence alone. He did not report measured refraction, leaving accommodation and convergence confounded in this work.

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Virtually all literature describing the formation of retinal images depicts a simple linear geometric relationship between the visual angle and retinal angle with its corresponding retinal image size (RIS). For the human visual system, however, such a simple geometric relationship is not completely accurate.

According to Smith et al. (1992), accommodation changes the distance between the back principal plane of the eye and the retina. The effect is that RIS is slightly and monotonically minified for all objects as a function of distance closer than infinity and magnified for dioptric values "beyond optical infinity." A much simplified (See Acosta, 1995a), but very nearly equivalent, linear approximation of this effect was incorporated in the data presented in Table 1. Essentially, contrary to classical theory, RIS is not constant for objects of equal visual angles at different distances. This simple and reasonable fact may be important and will be discussed again later.

The Size-Distance Invariance Hypothesis (SDIH), as defined by Kilpatrick and Ittelson (1953, p. 224) states: "A *retinal projection or visual angle* [note the explicit assumption of identity] of given size determines a unique ratio of apparent size to apparent distance." Stated differently, the perceived size of an object is predicted to be proportional to its perceived distance, when its retinal image size (i.e., visual angle) is held constant.

Epstein, Park, and Casey (1961) reviewed applications of this proposition in explanation of perceived size and distance and in specific accounts of size constancy. They point to two specific variations. The first, called the *known size-apparent distance hypothesis,* states that an object of known physical size uniquely determines the relation of the subtended visual angle to the apparent distance. The second, referred to as *Emmert's law* and mainly applied to afterimage studies, simply says that the judged size of the [retinal] image is proportional to distance *or* the apparent size of an object will be proportional to distance when retinal size is constant. Size judgments that reflect complete reliance on the angular size of an object regardless of its distance are said to conform to the *law of visual angle.* Size judgments that reflect an accurate determination of the object's actual physical size regardless of its distance are said to conform to the *law of size constancy.* Boring (1940) provides a clear and concise presentation of the logical and derivational relationships among these laws and apparent size.

In the prototypical experiment, Holway and Boring (1941) obtained size judgments under four conditions of diminishing distance cues. The stimuli and adjustable comparators were presented successively. Monocular size matches approached [size] constancy in high distance cue conditions and approached the law of visual angle with diminishing cues. Binocular matches under cue-rich conditions slightly exceeded size constancy with increasing distance. In this classic work, they dealt with relatively large distances (out to 120 ft.) and elaborated on perceptual judgments of size while systematically manipulating cues to distance and physical size.

In terms consistent with their experimental manipulations, they defined (p. 22) the *law of visual angle* to state, "accommodated objects which subtend equal visual angles are equal in apparent size....The size of the comparison stimulus (= apparent size of the standard) is equal to the size of the standard stimulus multiplied by the ratio of their respective distances." The comparator would be held at a constant size for a match regardless of the increasing distance of the 1-deg. standard. In contrast and using the same terms as above, the *law of size constancy* states that, "irrespective of their distances...the size of the comparison is equal to the size of the standard." Translated to angular terms, size constancy would predict a systematically shrinking angular extent for a unique object with increasing distance or, as in their experiment, comparator size would be increased proportionally with increasing distance of the 1-deg. standard (i.e., predicted slope of 1.0).

Size constancy, they argued, imposes stability for normal interaction with the physical world but is only possible when sufficient cues (*essential differentiae*) are available. They compared four conditions in a reduction paradigm, respectively: binocular, monocular, monocular with artificial pupil, and monocular with artificial pupil and reduction tunnel. Table 4 summarizes their findings.

Table 4. Size constancy versus the law of visual angle. Holway and Boring (1941) reported slopes of functions relating raw size of a variable comparator to match 1-deg. standard at selected distances (10 ft to 120 ft), instructions invariant.

Function: Size based on Distance:	**Size Constancy Prediction**	**Binocular Condition**	**Monocular Condition**	**Artificial Pupil**	**Reduction Tunnel**	**Visual Angle Prediction**
Slope	1.0	1.09	.98	.44	.22	0

This concept of sufficient "cueing" in the visual array to support accurate "perception" of such parameters as size and distance deserves elaboration. One convenient organizational scheme distinguishes cues that can be exploited monocularly or binocularly versus those that are emergent or specifically dependent upon binocular viewing. Parallax, the comparison of alternate views of the same scene or scene components from different perspectives and/or at different times for objects in motion, is not being addressed in this treatment. Table 5 below summarizes distance perceptual cue factors from Kling and Riggs (1971) and Wulfeck et al. (1958).

Recall (Table 4) that Holway and Boring (1941) found a slope of 1.09 for binocular size judgments out to 120 ft. under rich distance cue conditions. They attributed this unanticipated finding to a mysterious and unexplained

Table 5. Summary of cue factors affecting size/distance perception.

Monocular Cues:
Relative sizes of familiar objects
Knowledge of unique size of object
Aerial Perspective: Increasing attenuation and scattering of light with reduction in contrast from more distant objects
Linear Perspective: Systematic (geometric) foreshortening and convergence of physical dimensions and composite planes of objects with increasing distance
Texture Gradients: Systematic increase in apparent density of (planar) surface features with (assumed degree of uniformity of) component size distributions that foreshorten and converge (shrinking scale) in a manner consistent with linear perspective with increasing distance. Foreshortening in this case is critically dependent upon the relative slant or slope of the planar surface relative to the viewer (see Stevens, 1981).
Interposition or covering: Nearer objects occluding or shadowing farther objects occupying the same line of sight
Shadow and relief: Relative to real or assumed direction of light source
Figure-ground organizational discriminators: Smaller, higher contrast, more symmetric, vertically oriented, horizontally oriented, and/or convex subareas tend to be seen as figure; surrounding, nonsymmetric, lower contrast, and/or more concave regions tend to be seen as ground.
Grouping organizational discriminators: Spatial or temporal sequential proximity, similarity of component elements, trend and redundancy-based continuity, closure of apparent gaps
Motion Parallax refers to temporal-sequential views mediated by fixation point that provides depth cues through variable interposition and interpretable changes in optical flow and array of objects at different depths.
Binocular Cues:
Retinal disparity: Positive and negative sign cues relative to the horopter. Depth perception not contingent upon binocular fusion (Panum's area)

"space error." Gibson (1950) confirmed a tendency toward overestimations of size in high cue conditions at **comparator** to **target** ranges of 80 ft. to 675 ft., respectively, with the greatest overestimations between 80 ft. and 320 ft. Gilinsky (1954) replicated this finding out to 4000 ft., with the greatest raw metric overestimations involving a comparator at 100 ft. and the target at 400 ft.

Across a large number of careful experiments addressing the invariance hypothesis, researchers have compiled an impressive array of supportive and contradictory results. Gilinsky (1951), in one of her later experiments in a series, asked subjects to bisect each of 14 distances, ranging from 8 to 200 ft, by stopping a pointer that moved back and forth along the visual axis. Consistent with her earlier work, she found that perceived distance increases with true distance at a diminishing rate.

Carlson (1960), in defense of the hypothesis, maintains that findings of increasing overestimations of size with distance may be an artifact of "objective size" versus "apparent size" instructions. He argues that subject interpretations of known size and distance relationships confound their size judgments under "objective" instructions. He performed confirmatory experiments that seemed to support his position, getting more accurate judgments with apparent size instructions. Epstein et al. (1961), while conceding the criticality of instructions, challenged Carlson's results, noting that he failed to use a variety of distances to reveal the expected increasing estimation trend, if not the overestimations, even with apparent size instructions.

Gilinsky (1954) explicitly examined the effects of "objective size" (perceptual analog to measured scalar size) versus "retinal or projected size" (perceptual analog to measured angular size) instructions on judgments made over large distances (100 ft. to 4000 ft.). In her *objective condition*, the observer's task was to adjust the comparator to match the objective (tape-measured) size of standard objects at six selected distances in the range specified. In the *retinal or projected condition*, the task was to adjust the comparator to match the objective (protractor-measured) angular size of the standard, again at the selected distances.

Viewing conditions and available cues to distance were of high, real world quality. Size constancy would predict that the retinal instructions would result in systematically diminishing angular size with distance for any give unique real object. Size constancy would also predict that, regardless of distance, measured real size would not change. These are complementary concepts, consistent with experience.

Gilinsky's results, presented in part in Figures 11a and b, support, with some unexplained irregularity, the expected relationships between objective versus retinal size instructional effects, subject to the reservation that human observers are only fairly accurate and somewhat inconsistent/variable estimators. Her subjects generally overestimated objective size with increasing distance and she found that "the human being, at least without expert training, is not as accurate a measuring instrument as a yardstick."

Her subjects reported that "projected size" was very easy to give quickly and with great confidence. This in spite of the fact that with increasing distance, their responses were increasing in error relative to the Euclidean

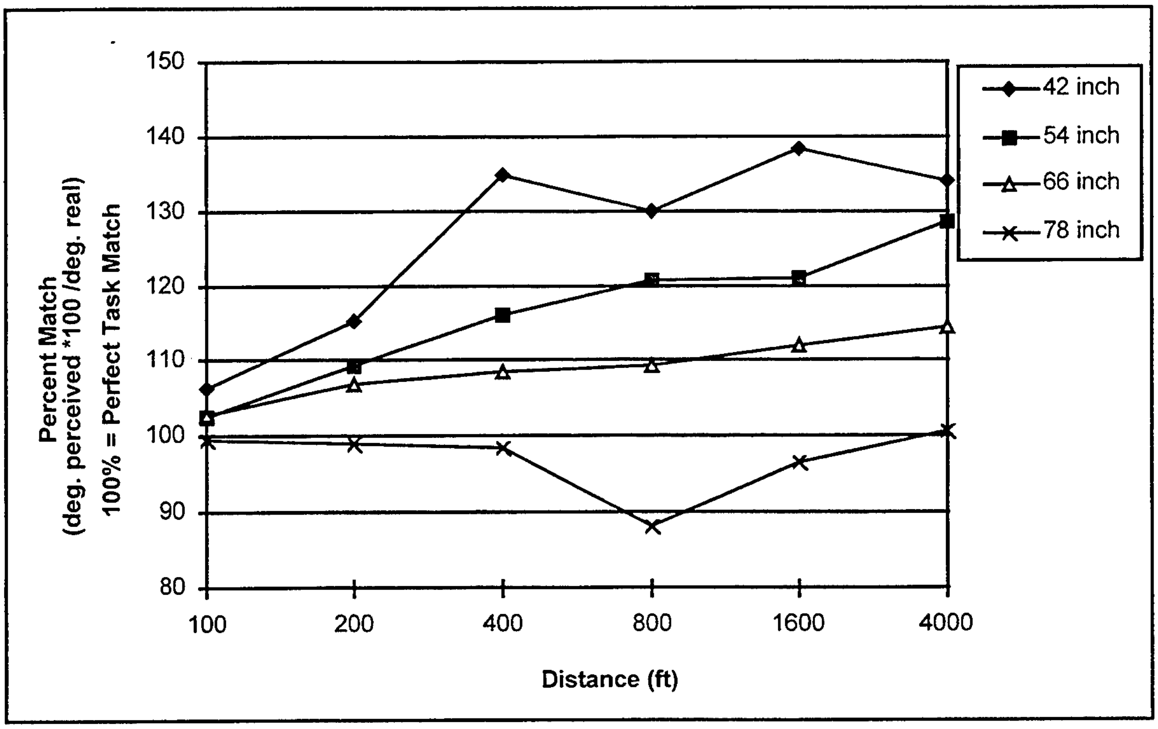


Figure 11a. Subjects were required to adjust the size of a comparator target at a constant 100-ft. distance, offset from a standard target line of sight by about 36.5 deg. Standard targets were positioned at indexed distances. Under "Objective" instructions requiring maintenance of measured size mentally corrected for distance, subjects generally overestimated real and, therefore, angular size. Increasing target size reduced the apparent magnification effect with distance. The 42-in. standards ranged from about a 0.05-deg. to a 2.0-deg. angle while the 78-in. standards ranged from about 0.1 to 3.7 deg. for farthest to nearest distances. Note that Gilinsky reports that the means for the 78-in. standard are artificially low because she did not include data for 6 subjects who, at unspecified points, needed to set the comparator larger than its upper bound of 86 in. Note also that, by inspection, either something interesting or erroneous is reflected in the mean values for the 42-in. target at 400 ft. and for the 78-in. target at 800 ft., both standard targets then subtending about a 0.5-deg. angle. (Adapted from Gilinsky, 1954, Table 1, p. 15).

response. In contrast, "objective size" matches were more difficult, especially with increasing distance. Subjects pressed for feedback in the latter condition and not in the former. While she did not elaborate on this finding, it is difficult to avoid the implication that feedback is a necessary condition for a closed-loop system to calibrate top-down, high-order estimators. This "seeking calibration" behavior may help define a critical boundary between primary perceptual and higher-order, cognitive-perceptual judgments as psychologically distinctive phenomena alluded to earlier by Wheatstone.

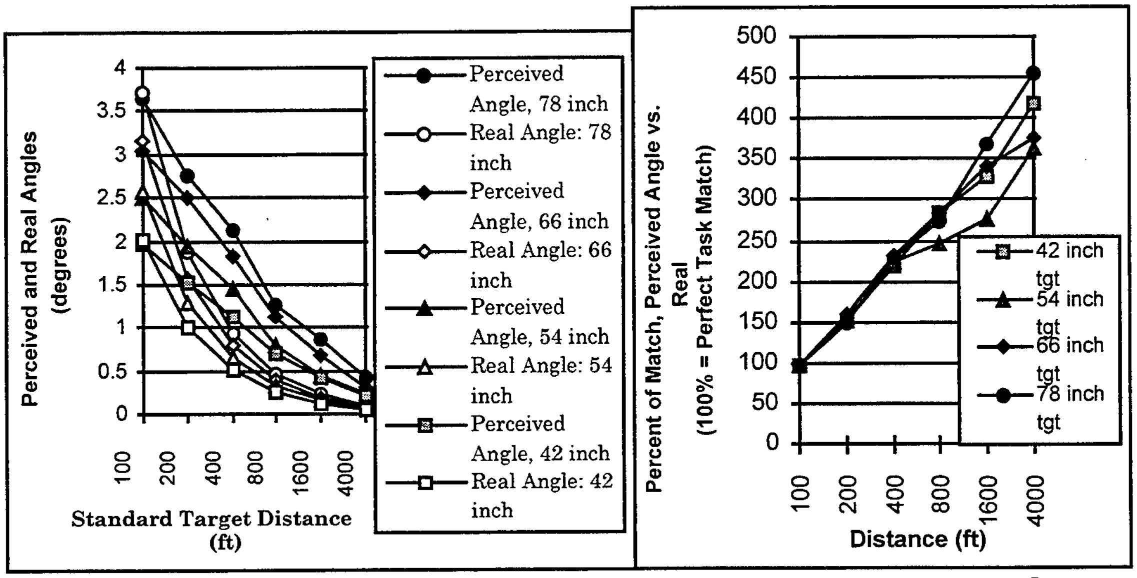


Figure 11b. Under "Retinal" instructions requiring correspondence of angular extent, subjects systematically overestimated angular size (adapted from Gilinsky, 1954, Table 1, p. 15). The right plot converted to relative perceived angle scores suggests a systematic linear perceptual trend on a (projected) logarithmic scale. The data, viewed in this fashion, reflect an apparent size magnification with increasing distance.

Logically and intuitively, objective instructions require that subjects explicitly estimate at least relative distance as **the** critical factor in estimating an objective size match. The distance estimation is at least one transformation removed from estimation of the angular size of the comparator at a fixed distance. Retinal or projected instructions require no such intervening activity. Angular size matches required only the limited imagery, memory, and response operations involved in switching from the standard's line of sight to the comparator's.

Though not critical, it is worth noting that while Gilinsky's choice of the triangle as the stimulus shape was ingeniously practical, this regular polygon was most affected by the acuity limitations of subjects for the resolution of height (size). The apices of triangles regress with distance at limiting acuity and make the sensible stimuli smaller and more circular. For example, assuming a 20/15 Snellen acuity, about 5 in. of the triangle tips would exceed acuity limits at 4000 ft. The amount of perceptual "correction" to retain the correct shape of the figure complicates the issue most for triangles. All regular polygons suffer this characteristic, diminishing in magnitude of effect as they approach a logical minimum for circles. Thus, regardless of the target shape, size judgment would be completely confounded with distance and individual acuity, but the triangle maximized the impact of limiting acuity on sensible height.

Based on her data, Gilinsky initially derived and then theoretically postulated the constructs called "*A*" and "d" (Gilinsky, 1989) as parameters that scale the differences between astronomical and estimable distances in real space, respectively. Her equations resulted in very good fits to the results obtained for the two instruction sets.

Gilinsky's *A* takes on values between infinity and zero. *A* equals infinity when, regardless of distance, perceptions of size strictly conform to measured scalar extent (the law of size constancy). *A* equals zero, when, regardless of distance, perceptions of size are strictly dictated by Euclidian angular extent (the law of visual angle). A is based on *interocular distance* and a threshold parameter of change in distance in object space. Gilinsky logically associates a large *A* with the expanded visual space perception of mature individuals relative to the reduced visual space perception of children.

Gilinsky's d is also an empirically derived parameter reflecting the object-and-individual-specific distance at which the selected object appears at its most "normal" viewing distance, corresponding to where it is perceived to be at its *true* size. So d is the distance at which the object is perceived correctly to be size S, its true size.

Gilinksy, applying the then conventional wisdom, specifically discounted accommodation and, initially, convergence as "inoperative or of negligible importance" at the (relatively long) distances involved in her experiment. It is interesting to suggest (and would be interesting to explore) a potential relationship between her A and d and the individually distinctive accommodative parameters of far point and tonic focus, respectively.

She does, to her credit, explicitly deal with interpupillary distance (her a) as predictive of the relative size of A, when combined with, in later reported derivations of d, threshold values of convergence (her g and m) to distinguish distant objects. The major disadvantage of her formulation is that it is restricted, by definition, from generalization to either predict individual differences or the expected effects of altered stimulus arrays; that is, all critical parameters must be derived independently from each individual under each specific stimulus array condition. She acknowledges but does not analyze the expected impacts of linear and aerial perspective, texture gradient, light and shade, monocular movement parallax, and stereopsis on all conditions of her experiments (Gilinsky, 1989). These variables are discussed in an appropriate aviation research context by Wulfeck et al. (1958).

Independent investigators (Hastorf and Way, 1952, and Chalmers, 1952) also found that with distance cues available, binocular overestimations of size increased at nearer distances and decreased at farther distances (i.e., a decelerating function of distance). This kind of curvilinear response is inconsistent with the traditional formulation of the hypothesis. More difficult than problems with the form of the predicted function, however, are direct contradictions.

Epstein et al. (1961) divided contradictory results into two classes. The first, *the size-distance paradox* (named by Gruber, 1954), is a consistent tendency either to couple an under-estimation of the relative size of an object with an overestimation of its relative distance or vice versa. The second class incorporates findings that a variable having a consistent influence on size judgments has no consistent influence on distance judgments or, alternatively, a variable having consistent influence on distance judgments is without influence on size judgments. The reader is referred to Epstein et al. for further discussion.

Ohwaki (1954) argued that the formulations of Gilinsky (1951, cited as the originator of a formal expression of the SDIH), and Holway and Boring (1941) should have accounted for critical physiological factors more explicitly. She attempted to manipulate accommodation as a variable with point of fixation instructions and manipulations.

Her subjects were instructed to fixate a 4-cm diameter, standard target at a fixed distance while four different-sized comparator stimuli, horizontally displaced in the same central visual field, were moved until the subject reported size matches. Under this condition, subjects very slightly overestimated the size compared to that expected based strictly on the expansion at a constant Euclidean angle. When subjects were given no strict fixation instructions or when a reduction mask was introduced limiting cues to the compared stimuli against a matte black background, the results were more variable with slightly increasing overestimation.

In her critical condition, however, subjects were required to change fixation point by 30-deg. to either side to observe the comparator in a normal-distance cue setting. This change in fixation was presumed by the experimenter to improve the accuracy of accommodation to the respective objects of fixation. Subjects responded in the direction of size constancy of the comparator, well away from the constant-visual-angle predicted values. Her conclusions, however, regarding accommodation and emphasizing its importance were not confirmed with appropriate dioptric measurement.

The Projection of Afterimages

Emmert's Law, the variation of the SDIH specifically applicable to afterimages, relates projection distance to the apparent size of the projected image. Consistent with the general conception of the SDIH, far projections result in larger perceived images. Size constancy should hold little sway in afterimage work since real (primary stimulus) objects are no longer involved at the point of critical size judgment (only retinal innervations, associated ocular mechanisms, and higher pathways). To clarify: real space, the visual array, defines and constitutes the surface of projection which specifies the real distance and size of any projection. The critical real world variable is the projection distance. The distance of this projection surface could, of course, be expected to impact focal distance (accommodation) and convergence.

Roscoe (1993) reports that his colleague, Bob Hennessy, formed successive afterimages of a stimulus viewed through a 1.5-mm pinhole placed at 8 cm in front of his eye. During the formation of the first afterimage Hennessy intentionally accommodated at 1/3 m (3 D or 63 D nominal); he accommodated to optical infinity (60 D nominal) for the second. The stimulus was a luminous square at 1 m, flashed twice in rapid succession. Hennessy perceived the resulting afterimages, projected at the *same* reference distance as differing in size by a ratio of 4 to 3, the infinity-accommodation-mediated projection being larger. Removal of the pinhole eliminated the reported apparent size differences.

As Roscoe points out, this did not contradict Emmert's law. Ray tracings, similar to Helmholtz's (see Figures 12a, b, c and d), demonstrate that

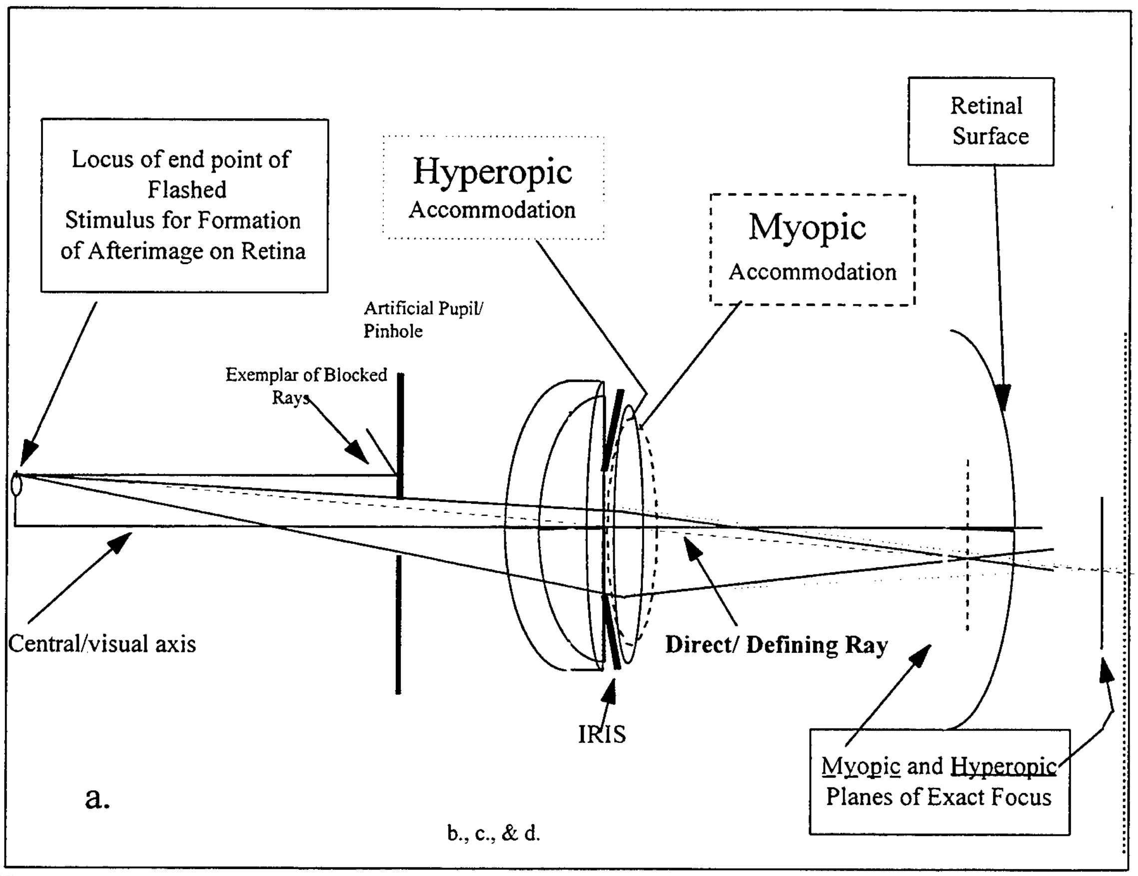


Figure 12a. Ray tracing illustrates that the point of exact focus for myopic, correct, and hyperopic lens configurations are roughly aligned at the appropriate retinal angle.

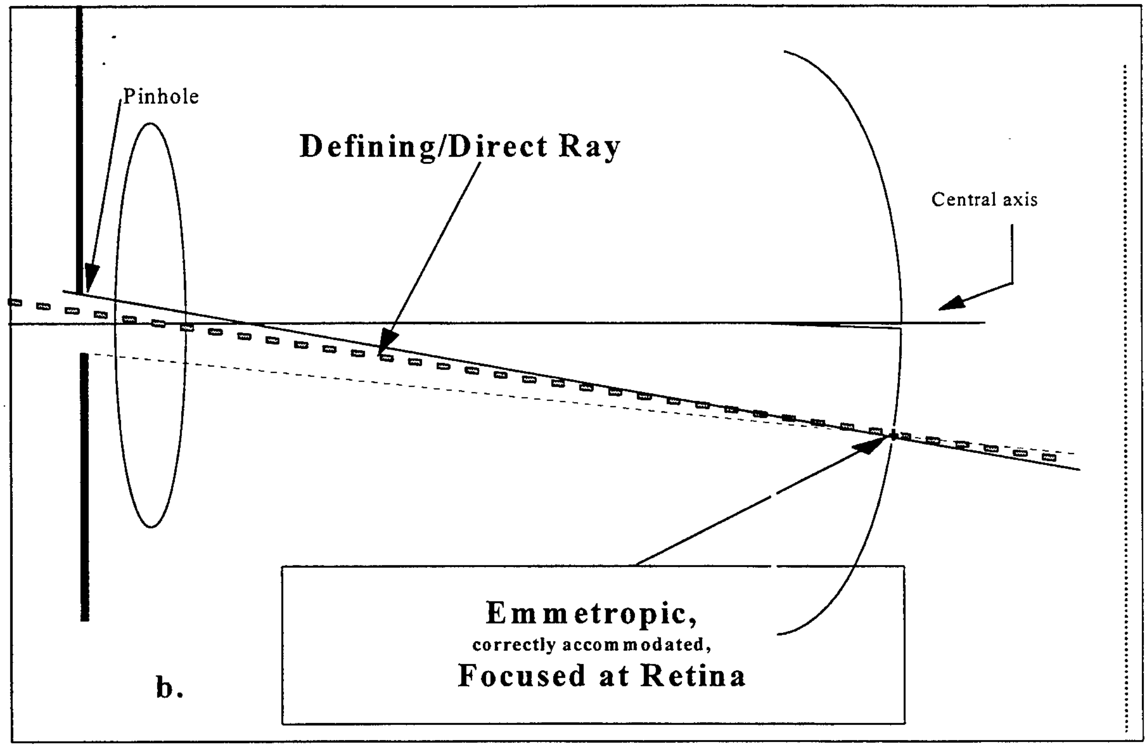


Figure 12b. Expanded illustration to clarify the locus of the off-axis end point of retinal stimulation for correct accommodation.

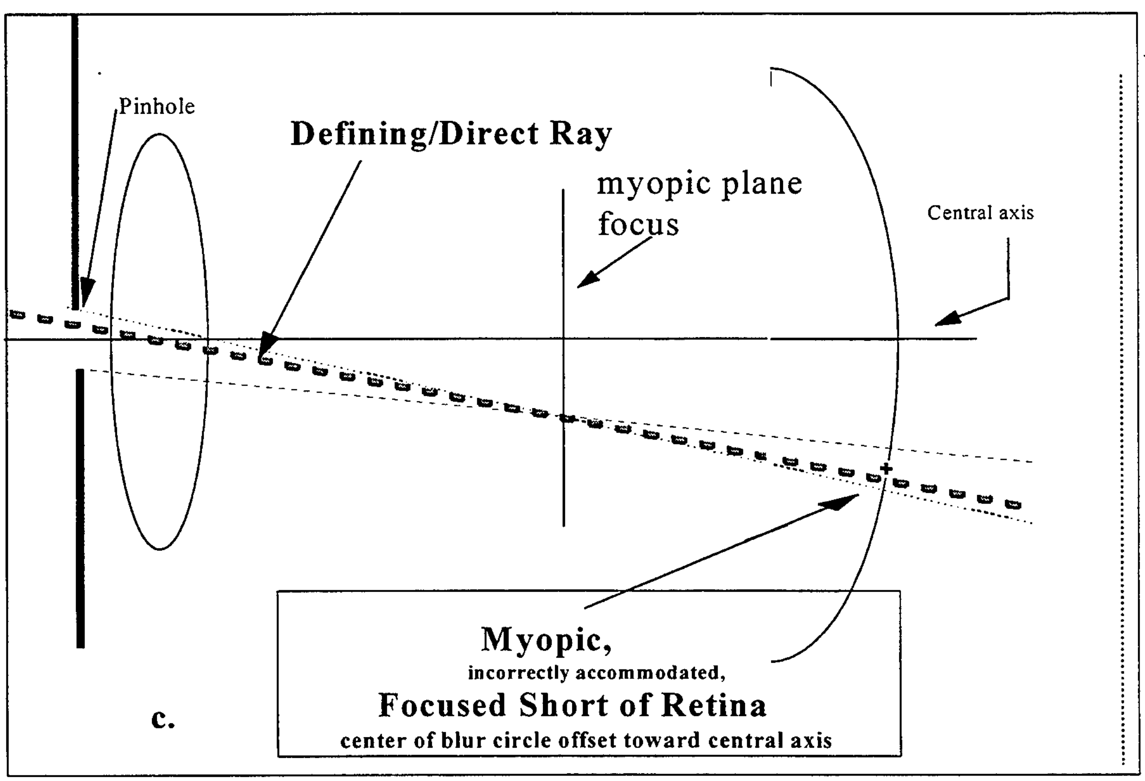


Figure 12c. Expanded illustration to clarify the locus of the off-axis end point of retinal stimulation for myopic accommodation.

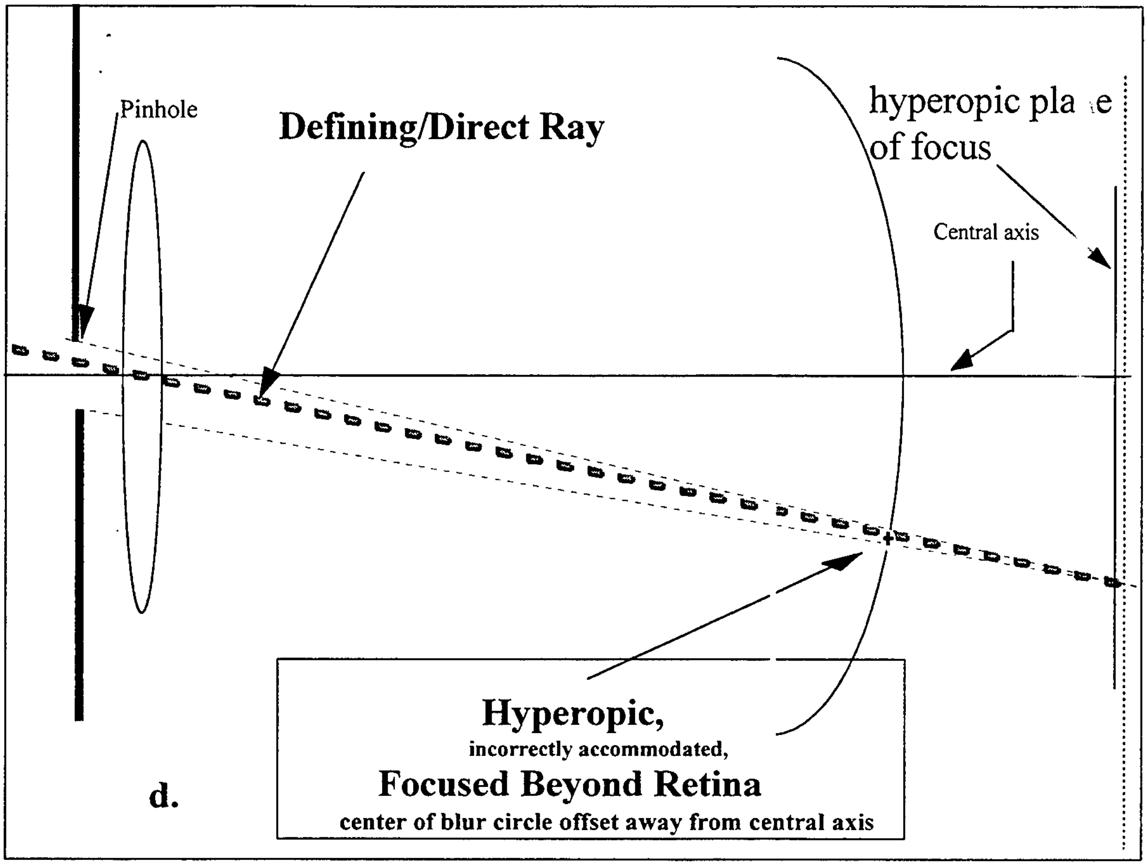
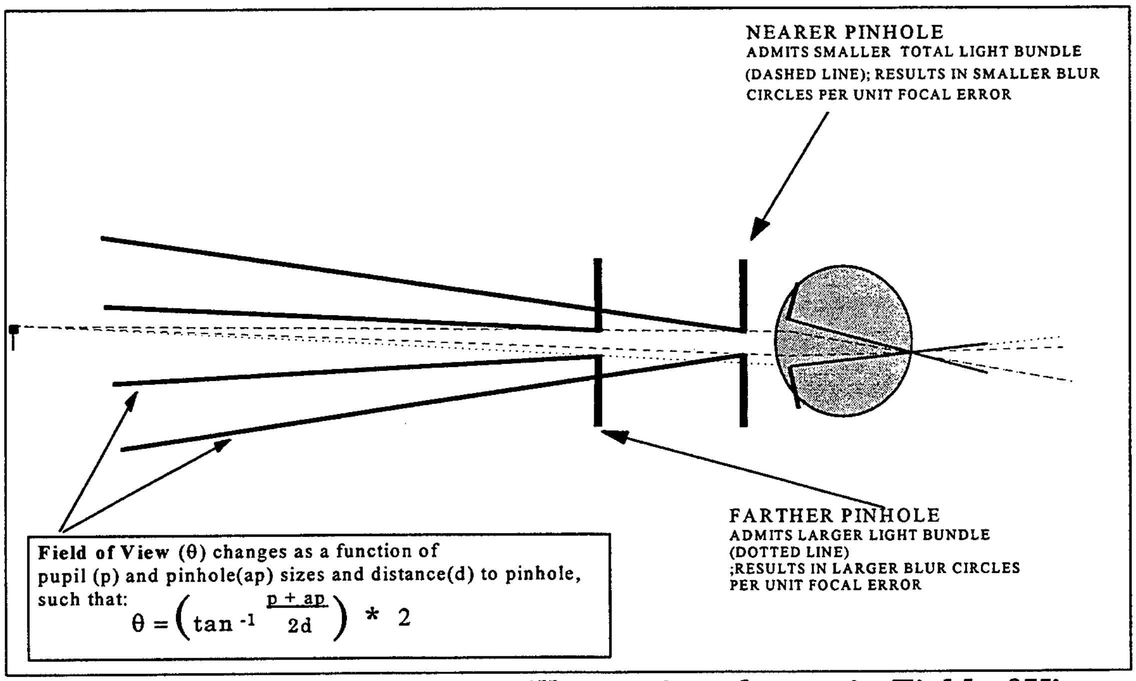


Figure 12d. Expanded illustration to clarify the locus of the off-axis end point of retinal stimulation for hyperopic accommodation.

the bundle of light limited by a pinhole that stimulates the retina is biased in central location by changes in accommodation. Shorter focal lengths of the flexible lens, all else held constant, shifts the center of the blur circle for all points from the object toward the central axis resulting in smaller retinal images. Analogously, longer focal lengths shift the centers of all blur circles away from the central axis, resulting in larger images. The subsequently projected afterimages were of different sizes because there were originally fewer or more, respectively, retinally stimulated photoreceptors. Since the projection distance was the same in both conditions, the projected afterimages varied directly with retinal stimulation. In personal correspondence related to technical review of this publication, Mr. Louis Corl has worked up specific calculations that predict (very precisely) the relative size effects reported by Drs. Roscoe and Hennessy. His formulations, to be published separately, demonstrate that the effects are completely defined by geometry outside of the eye, given the premises of specified changes in accommodation.

When the pinhole was removed and the process repeated, Dr. Hennessy reported that the afterimages appeared to be about the same size. Removing the pinhole eliminates the bias/asymmetry and reduces the accommodative effects on retinal image size considerably. With reference to Table 1, I would estimate that, for any given original target, there would be about a 0.5 percent increase in size of the retinal image (and a corresponding two percent increase in estimated total retinal cone stimulation) between the 1/3 m and infinity accommodations. The 33 percent difference reported for the pinhole condition defines a perceptual leveraging effect worth exploring, beginning with resolving whether the reported size difference was based on area or linear extent.

Longitudinal movement of a pinhole is interesting as a special case. As distance from a pinhole to the observer increases, the effective field of view through the pinhole diminishes (Figure 13). Pinhole movement, assuming constant accommodation, may give results approximately equivalent to changing accommodation with a fixed pinhole distance. The introduction of a pinhole in each case seems to move the nodal point of the optical system



$$\theta = \left(\tan^{-1} \frac{p + ap}{2d}\right) * 2$$

Figure 13. Simplified ray trace illustrating change in <u>F</u>ield <u>o</u>f <u>V</u>iew and diminishing ray bundle (shrinking blur circles per unit error in accommodation) with decreasing pinhole distance. Formulation is offered to compute field of view angle based on pupil size and the size and distance of an artificial pupil (pinhole). In technical review correspondence, Mr. Louis Corl pointed out that this formulation is for the <u>maximum</u>, not <u>useful</u> FOV. Mr. Corl offers that the useful FOV lies between the maximum value calculated above and a value calculated with the numerator term being "p-ap" (vs. "p+ap"). Without elaboration here, the difference has to do with the pinhole edges demarking "partial blur circles" that, at some threshold values, would exceed perceptual limits.

forward, away from the retina, increasing the retinal image size and with it the apparent object size out to a limiting case where the object exceeds the useful FOV. Concurrently, as illustrated in Figure 13., the bundle of light from a point on the object, and therefore the blur circle size, increases as a pinhole of any given size approaches the object. This is true out to the limiting case where the bundle of light expands to equal or exceed the size of the natural pupil (at which point the pinhole becomes equivalent to a very small knothole).

As in the prior example, the resulting percept may be further mediated by changes in accommodation, logically expected to either move outward with the pinhole or to regress toward tonic focus as blur size remains below threshold for (and the pinhole frame remains too near to stimulate) reflex accommodation. In addition, there might be a relative size effect based on the relationship between a unique object's increasing proportion of the shrinking field of view, or some variation of complex figure-ground, relative size, or framing effects.

All of the above considered, one conclusion might be that Emmert's law holds, subject to the conditions of accurate accommodation under normal viewing conditions. An interesting twist is that what changed in the demonstration by Roscoe and Hennessy was the *effective* visual angle (modifying the normal geometry through ray blocking) and, with it, retinal angle, augmented by the small change in retinal projection distance due to displacement of the flexible lens. The surprising result that the afterimages of a unique stimulus clearly differed in apparent relative size with the manipulation of the often discounted mechanism of accommodation, serves to dramatize what Helmholtz (1867/1962) discussed about retinal images of objects in real space over 100 years earlier.

The Moon Illusion and Accommodation

Since Ptolemy, serious investigators of visual perceptual phenomena have grappled with the readily observable contradiction of the moon appearing larger on the horizon and smaller overhead. They have proposed a variety of logic paths to explain empirical findings involving size and distance "perceptions." The universal nature of the illusion argues for its value in explaining fundamental visual perceptual mechanisms that affect operational and training performance. The clearly erroneous, but perfectly normal, perceptions involved in the moon illusion, have made it a serious phenomenon for investigation among human factors specialists for its real world safety, precision of performance, and transfer of training applications anywhere a human operator interfaces with a contact or analog display, whether immersed or not.

Over the centuries, widely varying motivations have lead some of the best minds in the world to grapple with the illusion and its proposed causation.

Plug and Ross (1989) elaborate on the brief summaries of approaches presented at Table 6.

Almost ironically, the **moon illusion** is commonly held to be the supposed classic and most studied exemplar for the **SDIH paradox**. The repeatedly confirmed and demonstrable facts are that the objective, Euclidean visual angle is not essentially different for the moon overhead (in fact, measurably slightly larger and nearer) and that there are no atmospheric lens or astronomical phenomena to explain the perceptual

Table 6. Brief summary of selected explanations of the moon illusion and its kindred phenomena. Based on Plug and Ross (1989).

Aristotle (384-322BC)/**Poseidonius** (ca. 100 BC)/**Strabo** (ca. 25 AD) Distance and air density cause a mirror or lens effect (refraction theory), so that the rising and setting moon, sun, and constellations appear larger than overhead. Additionally, sickness reduces all sensations because visual rays, generated by the observer in a kind of searchlight mode, are pushed out less effectively.
Ptolemy (ca. 142 AD) Moisture in the atmosphere causes refractive/lens/magnification effect, thickened at greater distance to horizon. "...the same angular distances appear to the eye greater near the horizon and smaller at the culminations..." (more refraction theory.) He logically rejected an astronomical position that held that the sun and moon arrive and depart at the horizon because they should have then expanded when "rising" and contracted when "setting," contrary to observations. Referred to observation on the horizon as "usual, normal and, therefore, a more correct, condition of vision" while overhead viewing is unusual and difficult resulting in erroneous viewing (angle of regard theory).
Ibn al-Haytham (11th century) The size of an object is judged by combining its visual angle with its known distance. Distance can only be judged accurately when **an uninterrupted sequence of intervening bodies** is present. An untextured surface will not suffice. The overhead sky is characterized as a plane, closer overhead and diverging and farther away at horizon. Clearly distinguished between real versus perceived enlargement (Intervening Objects Theory).
Greaves (ca. 1638), **Castelli** (ca. 1630's) Greaves, impressed by apparent differences between size in Egypt versus England, measured the real angular size of the sun at various elevations and found no change. Castelli did the same for constellations. (Counter to Refraction Theory)

Gassėndi (1636-1642), **Anonymous** (possibly Bourdelot, ca. 1672), **Young** (ca. 1807).

Gassendi first proposed a variation of a physiological optics-based enlargement of the retinal image for the horizon versus the elevated moon. His hypothesis (based in part on some erroneous speculation by da Vinci (ca. 1519) was that there was less brightness near the horizon causing an enlarged pupil and with it an enlarged percept of size. Bourdelot is thought to have attempted to explain the dilation effect by saying that it caused a flattening of the lens and a simultaneous lengthening of the projection distance (lens to retina). While this position was widely discounted by the mid-18th century, it awaited Young to disprove the basic mechanics proposed.

Berkeley (1709)

Berkeley held that both size and distance were judged from various learned cues. Among these were **aerial perspective** (increasing faintness and loss of color contrast with distance). Specifically addressing the moon illusion, Berkeley proposed that aerial perspective, variable under different atmospheric conditions, was *the* dominant determinant for the enlarged appearance on the horizon. Expanding on his *learned cue* theme, Berkeley proposed reduced size constancy with elevated **angle of regard.** Across a large variety of experiments, culminating over two and half centuries later with the work of Kaufman and Rock (1962), the effects of angle of regard seem to: 1. confirm an optimization of the human perceptual system to an *upright straight ahead* angle of regard, and 2. a very small, relatively insignificant, degradation in size constancy accuracy with departures from this orientation (i.e., not nearly enough to account for the illusion)

reality (see Minnaert, 1954, for discussions, demonstrations, and simple proofs).

The paradox arises when the horizon moon, with its essentially and demonstrably constant visual angle, is reported to be associated with a larger perceived size and reduced apparent distance. For visual angle to remain the same, both perceived size and perceived distance would have to change in the same direction, larger/farther or smaller/nearer.

A critical logical problem exists in associating the moon illusion with a SDIH paradox. It would seem that a paradox only exists if two errors are made, one in fact and one in formulation. The reported paradox as described by Kilpatrick and Ittelson (1953, p. 226) and more recently discussed, for example, by Hershenson (1989, pp. 2-3), stems from the standard SDIH prediction that a larger perceived moon (on the horizon) must be farther away than the perceived farther overhead moon, since both have the same real visual angle.

The first proposed error stems from a confusing denial of fact. Observers, when asked which seems closer, the horizon or the zenith moon, most often report, admittedly with hesitation, the horizon moon (Claparede, 1906; Dunn, 1762; Enright, 1989; Gryns, 1906; Haenel, 1909; Henning, 1919; Kaufman and Rock, 1989; King and Hayes, 1966; Plug and Ross, 1989). This is consistent with real world experience and with the Known Size-Apparent Distance variation of the SDIH. A solid object normally retains its real size and appears larger when it gets closer.

As long as "perceived" is operationally defined as "reported," these data must be resolved and would seem to be consistent with "real size when seen as larger, must be closer" and, thereby, consistent with the SDIH. One logical question implied is: "How much of what is reported in perception research accurately reflects critical sensory transformations affecting responses?" What if, in this example, unconscious processes take in a complex of sensory "cues," potentially initiating reflex responses which then, in turn, add to the potpourri that contribute to define conscious perceptions? If all of this happens quickly enough to feed rapid postperceptual precognitions, how could we perceive (in a metaperception) the differences among these hypothetical process modules? This is, in very general terms, the direction that a number of researchers have taken in the theoretical attempts to explain the moon illusion.

What if the horizon moon is (given its real and fixed size) fairly correctly seen as angularly "big," but also very far away? This would be consistent with the Euclidean reality. Why then, in a critical question for this formulation, is the moon seen as "bigger" (as opposed to just "big")? Well, as it happens in this same reality, this unique moon seen overhead is clearly seen as angularly smaller. In the two-horse race that ensues, the horizon moon is bigger. Roscoe (1989), Enright (1989), McCready (1986), Lockhead and Wolbarsht (1989) would argue it is misperceived as too small when elevated. Lockhead and Walbarsht specifically extend this in their "Toy Illusion" to "smallness" due to any open, intervening space. They have all argued a variation of the hypothesis that some preperceptual process has been fooled in a virtually universally compelling way.

Now, given that this overhead moon does appear smaller, a logical zero-order deduction for the observer would have to be that this unique moon had somehow gotten relatively farther away. The primary locus of the illusion as proposed here, and of particular significance relative to the SDIH, is at the percept of angular size. In this formulation, the key to resolving the cause is in defining the mechanisms that make it more likely for the observer to see the moon more correctly on the horizon versus anemic overhead.

Real objects cannot behave as do afterimages, increasing in size with projection distance. Apparent distance to real objects increases as they appear to shrink. A central issue then becomes, why would any real object appear to shrink, when it is not, in fact, getting farther away. Since this is the case with the moon, there is clearly an illusion, most logically involving the angular size of the moon, most probably, overhead. Application of the Emmert's law variation of the SDIH to real objects, seems inappropriate and diverts from the critical and logical examination of the correct portions of this problem's anatomy.

Rock and Kaufman have developed an elaborate argument that the larger moon is ***registered*** as farther away even if not reportable. See Kaufman (1974), Kihlstrom (1987) or Rock (1983) for discussions of subliminal perception, unconscious inference, and cognitive unconscious. This registration construct became necessary to "save" the SDIH from the devastating impact of accepting subject reports as accurate reflections of their perceptions in this particular case. The "save" is necessary as long as the relevant visual angle remains constant or as long as the primary locus of the illusion is at the horizon. Given the standard formulation, the only way the SDIH can hold is that both size and distance change proportionally. The entire issue can be traced to a simple but critical formulation that, at some subconscious level, observers really "know" that the visual angles are the same for the horizon versus overhead moons. Since it is "registered," however unconsciously, to be farther away, consistent with the SDIH, it is perceived as larger.

What is missing in the Rock and Kaufman formulation is the specification of any viable mechanism for this registration. What is proposed, instead, is mysterious knowledge of "real" visual angles.

Enright (1989) asserts that apparent distance is irrelevant and only "apparent visual angle" is critical to the moon illusion. He has proposed a multifactor, essentially oculomotor, model that emphasizes the coupling of accommodation, vergence and pupil response subsystems in precipitating a "near-triad zooming" and the moon illusion. His critical demonstrations involved the manipulation of apparent distance through the manipulation of the stereoscopic projection of virtual images in a binocular application of the Badal principle.

According to Hennessy and Leibowitz (1972) when the eye is placed at the posterior focal length of a positive lens, the projected virtual image of an object located between the lens and its anterior focal plane will always subtend the same visual angle regardless of the distance of the plane of projection and accommodation required. Optical distance, as a stimulus with accommodative demand, is a function of the distance of the object from the anterior focal plane. As the object approaches the anterior focal plane, optical distance approaches infinity. As the object approaches the lens, the optical distance approaches the focal length of the lens.

The relation between the optical distance of the image (Q' in D, "Q" corrected for optometric sign difference) and the target position relative to the lens (u, in meters), given the power of the lens (F, in D), is expressed in the formula:

$$Q' = F - F^2u. \qquad (5)$$

For example, to create the image with a Badal arrangement at an apparent distance of 1000 m (Q' = 0.001D) given a 30 cm (F = 3.33 D) lens, the target would be placed 29.991 cm from the lens. In practice, it is a simpler matter to "place" the image at any given distance by adjusting its position relative to real world objects at known real distances.

Applying this principle, Enright projected the image of a "moon" binocularly and stereoptically placed at a 3-km-distant horizon and then at about 60 m for a ratio of distance of about 50 to 1. Compared, for example, to the Kaufman and Rock (1962) magnitudes, the corresponding size judgment changes reflected a reliable but relatively small 10 percent reduction in size for the nearer target. When the experiment was replicated and the nearer distance projection was reduced to about 3.5 m, however, the corresponding size reduction was, on average, 3 times greater and more in line with Kaufman and Rock. Enright did not measure accommodation during these manipulations, leaving actual accommodation at issue.

Both Enright (1989) and McCready (1986) acknowledge that accommodation in concert with convergence may represent intervening mechanisms mainly through efference-based effects on perceived visual angles. However, they largely discount their influence based on the assertion that retinal image size effects of, mainly, accommodation are not "enough" to account for the illusion. Neither, it would seem, has recently conversed with a certain postulated vigorously gesticulating shade of Archimedes.

In agreement with Enright and McReady, it is proposed that it is neither logical or parsimoniously reasonable to treat perceived angular extent (apparent visual angle or angular size) as equivalent to perceived (apparent) linear size. Astronomers, in practice, refer to perceived angular extent as apparent size. In fact, no paradox exists if we simply allow the pivotal variable, visual angle, to assume its **perceived** manifestation along with (and distinguishable from) **perceptions** of linear size and judgment of distance, all in the context of size constancy. The definition of visual angle needs to be revisited, certainly in light of the Roscoe/Hennessy pinhole demonstration. If pinhole manipulations make it reasonable, even necessary, to reevaluate the basic geometry, why then shouldn't the dynamics of the mechanism of accommodation be questioned?

Since the moon has no compelling tendency to change its real, physical size, we can assume that most individuals "register" this fact at some fundamental perceptual/cognitive level. Once this point is granted, individuals are free to apply their SDIH behavioral bias to perceive (or more likely, judge) a more (angularly) extensive horizon moon as closer, consistent with both its real unchanging size and its directly apparent bigness. Rock and Kaufman (1962) elegantly and repeatedly demonstrated the preeminence of the quality of below-the-moon horizon features as critical to maximizing the relative largeness of the moon. What are the implications, then, if these same near-horizon features dominate the locus of visual accommodation?

One central issue is what goes wrong with the registration mechanism when we look overhead? While the concept of a registration of some kind to relate any unique object to its proper place in space seems appealing, accommodation (mediated by aperture size), ocular vergence, and the higher-order mechanism of stereopsis offer complementary primal candidates to provide both data and process mechanisms for converting sensed reality into perceptions for action. Shouldn't the majority of entries in Table 5, for example, be considered cues to accommodation and convergence prior to their relevance to size or distance perception?

Three questions immediately emerge:

1. Is there any systematic relationship between measures of these primal candidates and the manifestations of the moon illusion or related size-distance perceptual/psychological phenomena? ;
2. What are cues or interventions of operational and training transfer relevance that bias or influence the accuracy of primal candidate response (and, thereby, perception)? and;
3. What are the relative impacts of stimuli that affect graded responses of these candidates?

Plug and Ross (1989) refer to Rock's (1977) "perceived extensity" as the apparent size-based perceptual analog to real visual angle. The construct seems superfluous in that it seems to make a distinction without a difference. All that is really needed is to consider perceived visual angle as a logical dimensional component of perceived size (in some writings referred to as angular size). Misperceiving visual angle would define the illusion and give lie to the paradox.

Without these kinds of metric distinctions and disciplined consistency, a whole family of paradoxes might emerge--this one certainly has. The true illusion is that the apparent angular extent of the moon, any constellation of stars, or the sun on the horizon is compellingly perceived as clearly greater than the apparent angular extent of the same, unique object seen overhead. The judged distances are relative. If the illusion is confined to the overhead, too small, moon, it is its angular extent that is illusory. Size constancy and the SDIH would both dictate that the same real-sized moon must be perceived as closer on the horizon, as it generally is, and the erroneously shrunken beast overhead must be farther away. The illusion is more real than the paradox. It is suggested that the paradox that exists relative to the SDIH generally occurs when investigators mix metaphors and metrics--the paradox is an illusion.

ACCOMMODATION AS A CRITICAL INTERVENING VARIABLE

The Nebbian[1] Quest

Roscoe (1984) summarized a line of investigation that found its roots in his aviation psychological research on periscopic displays. He reported that periscopic displays required magnification on the order of about 25 percent above unity to effect landing approach performance comparable to normal contact flight. Roscoe, Hasler, and Dougherty (1966) reported that pilots had no tendency to overshoot or undershoot periscopic approaches made with an image magnificaiton of 1.2. Pilots in their study systematically overshot with a minified image, and undershot their approaches with a further magnified image. Subsequent research surrounding this special case of instrument micropsia led Roscoe to investigations centering on the mechanism of visual accommodation.

Roscoe, his students and colleagues (Nebbians, collectively), have reported on a series of studies that implicate the influence of individual parameters of accommodation (i.e., resting state, near point, and far point) and certain critical cue conditions for accurate accommodation on the consistency and accuracy of judgments of relative size. Consistent with the then recent emergence of experimentally practical optometers, Roscoe, Olzak, and Randle (1976) cited that theirs were among the first experiments done that measured visual accommodation while subjects were engaged in making size or distance judgments of foveally presented targets. Simple conversion of the dioptric measures of refractive state complete the linkage to distance as a de facto dependent measure, deductively implicated by equation to the SDIH.

The NASA-Ames experiments. In the initial phase of the Nebbian quest, Roscoe, Olzak, and Randle (1976) compared monocular and binocular performances at various distances up to 4 m. "Fancy" targets were circular disks imprinted with alternating flat black and white quadrants (i.e., wedges), adjusted in size to maintain 3 deg. of visual angle at each of the six distances used. "Plain" targets were flat white, untextured equivalents to the "fancy" targets.

The targets were presented under essentially mesopic (about 0.7cd/m^2) stimulus illuminance conditions. The "fancy" and "plain" targets were presented above a checkerboard textured gradient with white background or against an untextured (flat black) gradient and background. The texture gradient versus the untextured field were called the "high" versus "low" overall illumination (array) conditions, respectively. Since the angular

[1] Close friends and colleagues often address Dr. Roscoe as "Neb" or "Nebby." The appellation was allegedly assigned to Roscoe as a boy by a colorful uncle who called him "Nebuchadnezzar!" after he had delivered some rascally barristration. His immediate family seldom call him by any other name.

subtense was held constant, in a constant lighting condition total luminous flux on the target would be constant regardless of distance.

The task was a forced-choice as to which of two views, monocular versus binocular of co-distant targets, was larger. Not surprisingly, subjects generally judged "binocular-larger" with increasing consistency at increasing distance. Of greater interest, analyses indicated that the accommodation of the eyes is drawn toward the resting position when one eye is occluded. Further analyses indicated that size judgments are influenced by the direction and magnitude of shifts in accommodation for monocular versus binocular viewing relative to individual tonic focus. Effectively, the correlations between distance judgment shifts and a bias to tonic focus in accommodation seemed to be increasing out to 4 m. The investigators recommended an extended investigation of the functional relationships among distance and size judgments beyond the 4-meter limit of their experiment, accommodation, and textural distribution in the visual field.

At about this time in the evolution of the Nebbian quest, Roscoe first published his "Zoom-Lens Hypothesis" to explain a wide variety of disparate findings. It is essentially an oculomotor model (see Roscoe, 1977, 1984, 1985a, and 1993) asserting that refractive changes in the lens with accommodation change effective retinal size to systematically affect perceived size. As stated by Roscoe (1977, p. 25):

> ...it is my hypothesis that in addition to focusing the images of near objects on the retina, the function of changes in lens curvature for objects beyond the distance at which focusing is critical is to change the size of the projected image.

and earlier (1977, p. 1):

> It is hypothesized that relaxation of accommodation toward the intermediate resting position [read, *tonic focus*] in the absence of adequate textural cues to distance attenuates the size of the projected retinal image of more distant objects, thereby causing reductions in the apparent size or increases in apparent distance, including certain types of optical illusions.

This formulation became the centerpiece for the investigations that preceded and followed. Roscoe (1979, p. 729) distilled the central issues for resolution as: "...(1) the 'accommodation' of the eye can be forced or misled by several phenomena that can occur..., and (2) when accommodation is so disturbed, relative to the true distance of external reference objects, both size and distance perception are distorted....What can be done to reduce or overcome these effects?"

The Illinois experiments. During the Nebbian days at the University of Illinois, Iavecchia, Iavecchia, and Roscoe (1983), projected a 1/2-degree collimated "moon" onto a visual array as seen though windows of the 3rd through 8th floors of the campus Psychology building. They projected their moon onto a common scene that changed in angle of regard and locus of moon projection as a function of height above the ground. Their "moon machine" projected the collimated artificial moon onto a 45-deg. monocular (left eye) field of view or, alternatively, presented a comparator to be adjusted by the subject, in either case while permitting measurement of accommodation. The comparator and the moon stimulus were, therefore, presented separately in time, but along the same axis of observation.

Accommodation was measured during interactions involving a short duration (< 0.5 sec.) probe from a laser optometer. Outward accommodation and increasing size judgments corresponded until the moon just cleared the visible horizon in the view from the sixth floor, where both maximized. As the moon was projected farther above the horizon, both apparent size and distance of accommodation diminished.

In their second experiment, selective horizontal-masking confirmed that the critical distant feature to the most diminished illusion (least shrunken, i.e., biggest, moon) was the band of horizon immediately beneath the projected moon below the line of sight. As the texture gradient separated from the projected moon, the moon shrank in apparent size. The finding that the apparent size of the artificial moon behaved as it does with the real moon relative to the texture gradient reflects a critical and encouraging correspondence to earlier findings with natural stimuli and with projections in natural settings (Rock and Kaufman, 1962). The direct linkage to visual accommodation, reporting a Pearson $r = 0.89$, was unprecedented.

It is of interest that the highest relevant correlations were obtained with an inverse squared transformation of the apparent size raw data. This manipulation, most obviously, created more homogeneous distributions, approaching logarithmic-logarithmic comparisons. Less obvious are the implications related to area versus linear metrics and the candidate underlying mechanisms at work.

Hull et al. (1982) extended the Iavecchia work cited here and demonstrated that accommodation and size judgments were qualitatively and quantitatively different for collimated imagery versus real scenes, resolvable texture being most effective in real scenes. They compared accommodation and comparator size judgments of a projected collimated moon against a collimated, back-projected grid with fine lines versus a back-projected color image of a real campus scene and, finally, the real campus scene. Both the real and image campus scenes were masked to reveal texture features near, intermediate to, or well displaced from the scene horizon. They reaffirmed the Iavecchia et al. (1983) findings that the locus of the texture relative to the target of interest, specifically immediately below the line of sight, is most critical. They replicated the high correlation between mean apparent size and accommodation in the various conditions ($r = 0.97$). They took special note of the increasing variance of raw individual scores when apparent size is plotted as a function of accommodative shift from dark focus. Their data reflect significantly greater far accommodation to the natural scene in spite of the "collimation" of the alternative stimuli.

Interestingly, they obtained a "best fit" with a second order transformation of the accommodation measures. In the context of Roscoe's zoom-lens hypothesis, the implications in terms of a processing capacity orientation immediately and logically follow. Any increase in relative retinal image size should result in an increase in total receptors addressing this stimulation as a squared function of its linear extent. This linear extent is an inverse function of the relevant dioptric measures.

What might be the result of a theory-based area transformation (inverse squared times p) of the dioptric side of the equation? If, in fact, size judgments are more directly related as area versus linear extent to accommodative effects on retinal projections, such a manipulation should effect homogeneity of distributions in the direction of normal-normal as a statistically appealing side-effect. It would further help explain the effectiveness of the data transformation applied by Iavecchia et al. (1983) and might help account for some portion of the elusive variance discussed by Hull et al. (1982). Such a transformation could also be effected to eliminate the difficulty and scaling problems associated with negative dioptric measures and the compression of scale at far distances associated with all this work. Revisiting a theme from early in this presentation, dealing with accommodation as a critical intervening variable should reasonably pivot on projective effects within the eye versus the "corrective" metric inherited from the practical world of ophthalmology and elegant abstractions of theoretical optics. Estimations of relative areas of retinal projection would seem worthy of exploration.

Simonelli (1979), in addition to developing an excellent review of the dual innervation literature, specified a view that the psychological significance of tonic focus rests in its linkage to performance decrements associated with the variety of anomalous myopias. He explored the issue of the apparent competition between the variable adequacy or competition among stimuli in the visual array and the pull of tonic focus in defining the ultimate accuracy of accommodation. He pointed out that data reported by Sheard (1922) and Daveson (1972) among others, not only illustrated the "normal lag" of accommodation, undershooting accurate dioptric levels for near targets, but also revealed an unremarked "lead" in accommodation for targets beyond about 1 m. Significantly, as pointed out by Simonelli, crossover occurred at a point consistent with tonic focus.

As a final "link" in his introduction to his research, Simonelli emphasized the importance of psychoemotional and alerting states mediated through the autonomic nervous system to any interpretation of accommodative mediation in visual performance. Table 7 summarizes his and related exemplars.

Table 7. Selected findings relating autonomic nervous system stimulation/responses reflected in changes in visual accommodation. Generally based on Simonelli, 1979.

Researcher	Manipulation	Dioptric Response	Pupil or Vergence Response
Olmsted and Morgan (1941)	Startling tap on rabbit's nose	-1D, SNS discharge	NR
Morgan and Olmsted (1939)	1. Electric shock to human subject fingers 2. Shock to Electrician's finger, then loud noise	1. 37 of 54 subjects gave -D, SNS response 2. No response to shock, then -D, SNS, response to sudden noise	Consistent dilation of pupil (SNS response)
Pearcy and Allen (1927)	Expanded a balloon in human gut	-1D to -5D, SNS response	
Westheimer and Blair (1973)	Measured focus shift between awake to sleep and anesthesia	+1D to +1.5D, PNS, or lessened SNS shift	
Clark, Randle, and Stewart (1975); Randle (1975)	Subjects spun in chair for 30 sec. then measured accommodation open loop versus with far point fixation target	General myopic shift in tonic focus and slow (>10 sec) recovery to far point	NR
Westheimer (1957)	Subjected subjects to angering insults	+D, PNS, response lasting for several minutes	
Kelley (1962)	Threatened electric shock to children //Hypnotic suggestion to relax	Myopic, +D, PNS, response//Hyperopic, -D, SNS response w/ and w/o cycloplegia	NR// convergent response, +2D, inconsistent with accommodative shift
Kruger (1980)	Changed cognitive load for 20 of 40 adults from reading to adding 2-digit numbers at 40 cm	Myopic, +D, shift with increased cognitive load for 15 of 20 experimental group subjects	
Cogan (1937) anecdotal	Student, stressed about impending test, could not accommodate inward to text	Apparent SNS response opposing normal PNS functioning	

Vernier optometers and the Simonelli effect. Simonelli's first experiment confirmed the reliability and operability of a polarized vernier optometer, PVO. Of methodological interest, in this early implementation, the polarized components were unnecessarily situated along the visual axis, effecting no less than a 60 percent reduction in the total luminous flux reaching the eye under all conditions and introducing a noticeable "blur line" at the interface between polarized elements. These orthogonal polarizers effect the separation of the projected reticle into components to traverse contralateral pathways through the human lens system to recombine at the projection distance. This implementation of the Scheiner principle (See Helmholtz, 1867/1962, Vol. I, p. 125) results in an aligned vernier image only when the calibrated optics of the projection system correspond to the actual focal length of the subject's lens system when forming an image conjugate with the retina.

His second experiment examined the relationships among the acuity demand of stimuli, accommodative accuracy and individual dark focus. Both Snellen letters and modified Landolt C's stimulated increased accommodative distance with real distance (7.6 m) as a function of acuity demand determined by stroke (or gap) width. Generally, as acuity demand increased (decreasing size of stimulus detail) approaching threshold, accommodation moved outward. As acuity demand equaled and exceeded limiting acuity, accommodation once again regressed.

Low acuity demand (easier, big) targets, while easily read, failed to command precise accommodation, allowing lapses in the direction of tonic focus. Interestingly, in a finding that Roscoe (1985a) would later dub the "Simonelli effect," subjects with extreme far points (beyond optical infinity), while demonstrating the same overall trends described above, actually focused (optically) beyond the real stimulus distance, beyond infinity in many cases for even the least demanding stimuli. Roscoe (1982, p. 975) concluded that ..."acuity in resolving distant stimuli is enhanced by focusing at a distance greater than that of the stimulus to be discriminated ... for individuals capable of unusually distant focus." This finding deserves a special discussion.

The nature of the PVO effectively creates two optical objects of a single line segment, the orthogonally polarized images of line segment halves. The refraction of light through the human lens system, reasonably assumed to be symmetrical bilaterally, will result in an aligned pair of lines at a unique distance from the PVO lens system that corresponds to its current effective focal length. This focal length may or may not be conjugate with the retina and is completely defined by the character of the light projected into the eye by the PVO and independent of the object of accommodation of the eye. The PVO projection is intentionally presented for an interval too short to permit closed-loop accommodative response. This means that what is being indicated when there is vernier alignment is the state of refraction of the human eye given its current fixation target, independent of the PVO stimulation.

The Scheiner principle dictates that whenever the plane of exact focus of the PVO reticle is not conjugate with the retina, the optically distinct components will not be aligned **on** the retina **and** will be out of focus **at** the retina. A potentially important distinction is being made here. Real world or projected continuous line segments (not artificially made distinct though polarization as by the PVO), being optically equivalent and continuous, would be expected to be out of focus **but** would remain aligned.

Beyond "optical infinity." Negative dioptric measures taken while subjects have fixated optically demanding real world objects (at or nearer than optical infinity) imply special interpretation. A negative dioptric measurement means light behaves as though the image converges to/from a point behind the subject's head at a distance equivalent to the reciprocal of the dioptric value. In practical terms, the convergent light being projected into the eye would normally focus at a plane well in front of the retina. Since the subject has reported that the vernier line segments from the PVO are aligned, they are, by definition, conjugate with the retina. The light, however, coming at the same time from any natural part of the visual array is, at most, effectively parallel, if not divergent, as it enters the eye. Logically under this condition, the resulting images from natural space must be optically focused behind and blurred at the retina. Since the subject's primary task is to focus the fixated real world target clearly, the measured phenomena and the perceived phenomena would seem to be different in some fundamental way.

One alternative would be to speculate that some non-optical, **psychological process** behaves like an additional lens or filter to enhance the image from the real world, at the expense of the optical focusing of the retinal conjugate image, to achieve clarity and higher effective resolution. The retinal stimulation from the real world target will be blurred on the retina, but also expanded. This would happen through the mechanics of the changing projection distance to the retina discussed earlier, the retinal contraction accompanying more distant accommodation, and by the peripheral half radii of blur circles formed. While an increased area and density of retinal receptors and, consistently, more higher pathway neural components are engaged, the total information in the optical array has not changed. Logically, though not entirely intuitive or comforting, some information processing advantage might result at the level of perceptual integration.

Earlier investigations confirm a considerable limen or range of blur-tolerance for the human visual system. One need only assume that while level of effort might dictate a bias toward tonic focus, acuity demand might dictate a competing bias toward effective magnification. Long after any optical effect might come to bear (e.g., with age), the increased processing capacity advantage might overbalance the additional effort required to command outward accommodation. Modern technology has demonstrated that image enhancement of blurred imagery can occur to the informational limits of the optical system (e.g., the Hubble space telescope and a large variety of land-based optical telescopes) given appropriate deformable compensatory optics and sufficient transformational and computational power and time. However skeptically, such a "psychological lens" concept would seem worth consideration in light of accumulating evidence.

The population of eyeballs. Departing this discussion for now, Simonelli highlighted the criticality of distinguishing individual differences in visual parameters, especially dark focus and far point, prior to generalizing the results of any given sample of subjects from the population. He found a correlation of .97 between far point and dark focus and demonstrated that, as would be expected, either measure dictates the position of any given subject's response function.

In his next experiment of this series, Simonelli (1979) examined what he defined as the *relative dark focus,* the dioptric range between dark focus and far point, across a variety of ametropic subpopulations (emmetropes versus myopes versus hyperopes), most specifically between generally myopic university students and more emmetropic/hyperopic Air Force recruits.

Simonelli pointed out that for a strong myope, for example, measurable far point might be as close as 4.5 D (22 cm) with a correspondingly near dark focus of 4.8 D (21 cm). Anything beyond the far point would be, by definition, out of focus through the physics of optical dynamics (relatively too deep eye depth and a relatively too powerful lens system). Even with this fairly close far point measure, with a near point for a young myope in the range of about 10 D (10 cm), the total dynamic accommodative range would be a reasonably large 5.5 D. For a strong hyperope, a near point of .33 D (3 m) and far point of a rather extreme -2.0 D dictates a fairly anemic dynamic range of 2.33 D, most of which does not correspond to natural optical array conditions. Across 268 subjects, Simonelli found a mean (laboratory-measured) far point of a surprisingly close 1.09 D (92 cm, 61.09 D nominal) ranging from -4.5 to 12.6 D (sd = 2.01) and measured dark focus averaged a myopic 1.82 D (55 cm, 61.82 nominal).

Relative dark foci (effectively selected, restricted range measures), which averaged 0.71 D, ranging from 0 to 2.8 D (sd = 0.53), tended to shrink with age and did not discriminate between subgroups, not surprising with the high correlation between far point and measured dark focus. Simonelli's data confirmed a large recession of the near point, and much more moderate recession of dark focus and far point with age, and, of course, the resultant reduction in total accommodative range. He found that, in comparing young students to young recruits (relative hyperopes), while near points did not differ reliably, far points did. When he restricted the above comparisons to those with acuities of 20/25 or better (a fairly typical experimental screening and emmetropic criterion), far point no longer reliably discriminated the two groups, but near point did. Applying this criterion had eliminated 70 percent of the student sample and only 32.5 percent of the recruit sample. The recruits, as a group, enjoyed a decidedly greater overall dynamic range of accommodation.

The Mandelbaum-Benel effect. Benel (1979) at the University of Illinois picked up on the work of Mandelbaum (1960) and Owens (1979) and discovered a surprising connection between this earlier work and the moon illusion. Mandelbaum had reported a phenomenon bearing on our ability to accommodate accurately, and Owens had established a relationship between the so-called Mandelbaum effect and individual differences in tonic focus. Mandelbaum (1960) observed that when he viewed a distant sign at some critical distance from a normally transparent and unnoticed screen, lettering on the sign blurred. He resolved to study the phenomena and, when the opportunity presented itself with a visit to a house with a perfect porch screen and distant sign, he did.

Twenty-one observers, ranging in age from 9 to 57 years, reported the onset, maximum, and offset of blur of a distant (relatively high acuity demand) target when viewed at various distances from an intervening porch screen. Onset and offset of blurring ranged from about 0.45 m to 2.4 m, respectively, with maximum blur experienced between about 0.9 to 1.8 m. He induced cycloplegia and maximum pupillary dilation to confirm that the phenomena specifically involved accommodation. He concluded that the porch screen, at a critical distance that was consistent within individuals, caused an "overwhelming stimulus for accommodation." He further speculated that the appearance of imperfection, dirtiness, and other blemishes on windshields might have more of an impact on perception of distant objects then mere interposition.

Benel (1979), following a suggestion from Owens, explored the viability of regression slope as a metric of stimulus adequacy for accurate accommodation and, in turn, accommodation's relationship to size judgments. In the first of a series of experiments, he manipulated stimulus contrast and formally demonstrated that decreasing contrast resulted in systematic regression toward tonic focus. He measured both empty-field (Ganzfeld; see Whiteside, 1957) and dark focus, with matched and mismatched light levels at the unmeasured eye. While he found that there were reliable but small differences between these indicators of tonic focus (consistently nearer for darker), the measures were reliably and highly correlated (r's ≥ 0.59). His measure of "matched dark focus" (nominalized at 63.7 D) best approximated the "fulcrum" value of accommodation about which the contrast-specific response functions pivoted. To clarify, when actual accommodation was plotted as a function of target distance, the slope of response functions for each level of stimulus contrast approached zero for the poorest contrast and one for the highest, all regression lines pivoting about the group mean dark focus. He noted that the quality of his Ganzfeld may have contributed to the differences measured but that "construction of an adequate binocular viewing system would not have been a trivial matter."

In his second experiment, Benel explored the effects of Mandelbaum-screen and target-distance manipulations on accommodation. As in his prior experiment, all distance manipulations were "optical," using lenses in a Maxwellian view arrangement (see Westheimer, 1966b). His hypothetical position was that a general regression toward tonic focus would occur as a direct function of the proximity of the Mandelbaum screen to individual tonic focus, mediated by the quality of the Mandelbaum screen (a function of screen contrast) and the magnitude of the difference between target and screen distances relative to tonic focus. The Mandelbaum effect was expected to be maximal when the "best" screen was at or near tonic focus and far from the presented target. His findings generally supported this position, although the picture that emerged reflects that, while the locus of tonic focus presented a consistent vector, so too did either of the stimuli presented (i.e., the screens and the target).

Benel's third experiment generally replicated the Roscoe et al. (1976) study, asking subjects to compare targets (a Snellen-like letter array) at selected optical distances with and without a simultaneously presented optimum Mandelbaum stimulus. Subjects were permitted to give a "no change response," thereby increasing the response resolution over the prior effort's binary, larger versus smaller, options. Shifts were reliably ($p \leq .02$), though not exclusively, in the directions predicted for a regression toward tonic focus. "Smaller" size judgments were consistent with nearer accommodation 69 percent of the time and with farther "larger" for 75 percent of the relevant trials. The "no change response" approached even odds of being associated with a nearer versus a farther accommodation shift.

In his fourth and final experiment in this series, Benel used the apparatus and one scene used in the earlier Iavecchia, Iavecchia, and Roscoe (1978) study to project an artificial moon and present a variable comparator for size judgment. A typical (dark fiberglass) screen, when presented, was placed at a distance of 1.33 m or 0.67 m or 0.44 m or 0.33 m. In conditions without the screen and across the four screen distances, the correlations between accommodation and apparent size were reliable ($r = -0.56, p < .05$; $r = -0.76, p < .01$, respectively). For combined data, averaging 12 observers' responses, Benel reports an $r = -0.96$, reflecting apparent size (in degrees) as a function of accommodation. The intercept of the corresponding linear function (inverted to reflect accommodation) was 63.34 D nominalized, fairly consistent with his sample's average tonic focus. He observed that the monotonic increase in mean accommodation as the screen approached, when combined with the high correlation between apparent size and accommodation, suggested that accommodation may be a "prominent factor" in the perception of size.

Head-up virtual images. Iavecchia, Iavecchia, and Roscoe (1988) investigated the effects of viewing collimated, virtual, head-up display (HUD) symbology against a distant outdoor vista and against simulated clouds. Whenever the HUD symbology was "turned on," it biased responses toward individual tonic focus relative to the stimuli in the outside scene. The majority of explained variance was attributable to tonic focus. Subjects with 20/20 acuity or better demonstrated large individual differences in focal distance mediated by the loci of their far and near points for equivalent (perceived as "in focus") targets. While the authors offered not even a tentative explanation, it would seem logical that either "turning on the HUD" stimulated nearer focus or somehow "neutralized" the stimulus value of the distant scene. The mechanism of the latter might work somewhat along the line of a Mandelbaum effect. The possible mechanism of the former requires more radical speculation.

The typical HUD uses a combining glass, flat and tilted to the visual axis. The combining glass reflects a projection from a lens, so positioned that the rays of light from a single point on the image departing the lens are "parallel." The traditional "optical" interpretation of parallel rays is that they behave as though any given point on the object in real space, the apex of a hypothetical triangle, is so far away that the relative size of the base across the pupil is so small that the interior angle approaches zero and the exterior rays approach being parallel. However, in real space, any point in the visual array peripheral to the central visual axis more than the width of the pupil will emit a distribution of sensible light rays that converge on the pupil from real space or miss it entirely.

Recall the Stiles-Crawford effect and the eye's structurally-mediated sensitivity to direction or relative azimuth of incoming light. What if the HUD, with its typically flat, fronto-parallel reflecting surface, is stimulating our directionally-sensitive retinal system with lens-mediated light that is, beyond a frontal extension of the physical width of the pupil, distributed "differently" relative to light emerging from natural distant objects? In fact, what if this "mis-vergence" mimics, however poorly and unintentionally, the kind of light distribution the eye senses most typically when objects are, in fact, very close to the eye? A Mandelbaum screen, might very well function in an analogous fashion, something like an array of pinholes, mimicking a collimating effect.

One way to test this speculation might be to examine the effects of systematically curving the HUD (combiner) reflective surface while measuring the accommodative response of the eye. Such curving would effect varying degrees of "planned" distortion of the image, including magnification effects (both positive and negative) that could be varied with degree of eccentricity. An alternative to a HUD combiner might be an array of pinholes in a flexible array. A point of departure for such an investigation might be data from empirical horopters. By analogy, the kinds of imagery/optics augmentation now being widely used in astronomy and astrophysics, turned outside-in, might help explain and, eventually, compensate for the kinds of perceptual phenomena being addressed here.

Continuing a line of discussion related to virtual imagery effects, Norman and Ehrlich (1986) reported that 19 emmetropes, on average, needed display adjustments to -0.5 D to report clear focus at actual accommodation to optical infinity during a target detection and recognition task. As with the eye's lagged responses to the introduction of artificial lenses, projected images apparently failed to "demand" one for one responses by the accommodative system. The authors reported that tonic focus clearly affected the extent of measured lag of accommodation.

As part of a series of field studies evaluating the operability of a micro-vernier-optometer (MVO), Roscoe, Corl, and Couchman (1994) measured far-point responses to real versus projected virtual stimuli. While their limited sample of eight subjects presented a wide range of individual differences, all accommodated farther out and, generally, more accurately by almost 1 D to a real desert vista than to virtual stimuli. The reported correlation between dioptric focal demand (far point lens settings) for the virtual imagery in the focus stimulator and measured accommodation was 0.71; the correlation between the accommodative responses to the virtual imagery and the corresponding measured accommodation to the desert vista was 0.89.

For the real scene bounded at optically infinite stimulation, their average natural far-point, fp_n, response was 0.41 D (60.41 nominalized, 2.44 m), ranging from 0.89 D to -0.17 D. For virtual imagery, the dioptric setting of the focus stimulator was 0.03 D, ranging from 0.52 D to -0.54 D while the corresponding accommodative responses (laboratory far-point, fp_l) averaged a myopic 1.37 D (61.37 nominalized, 0.73 m) with a corresponding range from 2.25 D to 0.81 D. The simple correlation between laboratory far-points and natural far-points is .88 in this experiment, leaving 23 percent of the variance unexplained (*estimated* $fp_n = (-0.46) + 0.64 * fp_l$).

Moffitt (1985) explored the independent impacts of refractive error (3 levels of interposed lenses set at and $\pm$ 1.5 D of subject accommodative responses to a reference target) and accommodative demand based on Badal projections of a texture grid at 3 distances (33 cm, 2 m, or infinity). Primary stimuli were three sizes each of "Tumbling E's" for a resolution task, and untextured discs for a detection task. Both stimulus types were viewed through an aperture at the center of the peripheral grid. Detection sensitivity was measured as a function of threshold target illuminance manipulated using neutral density filtering. The size judgment data and results were limited to unanimous subject reports that farther accommodation was associated with the larger perception of grid size, nearer with smaller.

Consistent with Moffitt's hypotheses, higher refractive error and higher levels of optical density filtering negatively affected resolution and detection performance, especially for smaller targets. The peripheral texture, in the presence of centrally presented targets, failed to affect levels of accommodation, thereby failing to support Moffitt's predictions concerning 1st and 2nd order interactions.

Based on his results, Moffitt recommended that future studies should ensure representation from that subpopulation with high negative dioptric far points, echoing, in part, Simonelli's cautions. Methodologically, he suggested that: (1) texture and target should be combined to increase the range of accommodative response, (2) accommodation should be measured in conjunction with stimulus manipulations, rather than "assumed," based on prior stimulation level effects, and (3) variable contrast ratios might provide meaningful manipulations to avoid restriction of range effects, based on individual differences. Moffitt further noted that the traditional Snellen measure of far acuity failed to correlate with any of his other optometric or performance measures. He suggested that other tests of visual function be explored (e.g., contrast sensitivity).

Volitional focus control. Randle (1985) and Roscoe and Couchman (1987) attempted to train subjects in the volitional control of accommodation with varying degrees of success. Beyond demonstrating feasibility, their ultimate goals were to convert volitional focus control and extended far-point into improvements in operational performance. Randle's findings suggested that myopes presented difficulties in terms of extent and retention of "skills" developed through training. All training proved to be somewhat labor-intensive, especially with the infrared optometer employed for this work. Roscoe and Couchman found that, after initial training and when combined with a variable focus stimulator, the less-restrictive polarized vernier optometer promised faster and easier training. They observed, however, that, as with any "muscle-conditioning" program, skills maintenance and improvement are likely to require extended and dedicated "exercise."

Visual performance in air defense. Barber (1989) examined the relationship of ocular-motor attributes and parameters to visual performance in air defense tasks for potential selection and classification applications. As a theoretical basis for his work, Barber discussed a *Three Visual Subsystems Hypothesis* (per Livingstone and Hubel, 1987). Consistent with earlier discussions and particularly relevant to Barber's air defense applications, the three visual system functional allocations roughly correspond to detection, identification, and tracking, respectively.

The three subsystems are:

1. The magnocellular pathway, which processes low spatial frequency, high temporal frequency, low luminance, and low contrast information, employing the parafoveal retinal input.

2. The parvocellular pathway, which processes high spatial frequency, high contrast, color, low temporal frequency, and high contrast information, originating at the foveal region of the retina.

3. The interlaminar pathway, which may provide complex integrations of information about features and spatial relationships among objects.

Based on earlier work, Barber predicted and found high positive correlations between visual acuity, contrast sensitivity, far tonic focus and far point with superior air defense detection and recognition performance. He predicted factor analytic results that would correspond to the three pathway hypothesis. Accordingly, he extracted three principal components defined as: **passive accommodation**, predicting target detection and acquisition; **active accommodation**, predicting target detection and identification; and **image interpretation**, predicting acquisition, identification and tracking. His findings suggest that applications of visual accommodative performance measures to selection and classification for selected skill and task profiles are both feasible and advisable.

Accommodation and the locus of the optical blind spot. Roscoe (1989) described a series of experiments relating accommodation to the mapped locus of the blind spot and judgment of apparent size as functions of distance to a stucco wall or a desert vista as an alternative projection plane. In the initial experiments, increasing distance to the wall (where the blind spot was mapped) resulted in systematically, though lagged outward accommodation and significant angular displacements and changes in extent of the blind spot. Both the extent of the blind spot and its angular displacement from the central axis decreased with increasing distance. He reports a correlation of -0.99 between mean accommodation and the mean angular position of the blind spot. This finding is consistent both with the logical effects of outward accommodation on effective retinal image size (i.e., the image should be relatively larger) and the implications of the earlier cited work on retinal stretch (i.e., effective receptor density should increase, per Blank and Enoch, 1973, and Enoch, 1973).

In the second set of experiments, the blind spot was mapped at 1 m, while subjects estimated the apparent size of a projected "moon" at varying distances against a desert vista with its far horizon or variable-sized letters presented at distances from 1 to 30 m and positioned above the horizon. While the blind spot mapping data were noisier and demonstrated less dramatic size changes, the high correlations between locus of accommodation and blind spot measures and target size judgments prevailed (reported r's $\geq$ 0.81).

Toward a Conceptual Framework

In sum, the efforts of those who have researched this area have given us the benefit of at least two inescapable vectors. First, the effectors surrounding size and distance perception are complex and highly interrelated. Too narrow a focus and we'll miss what's happening entirely. Second, evidence from multiple disciplines converges on the binding conclusion that the accommodative mechanism may be a pivotal intervening variable. It presents a nexus (needing clearer specification) between higher and peripheral mechanisms from which we might learn a great deal.

A multiple bias/centroid theory. In attempting to deal with the wealth of data implicating accommodation as a significant intervening variable in the primitive perceptual behaviors of size and distance judgment, several observations are relevant. ***First***, the data indicate that accommodation is often imprecise relative to real object distance and there is a significant and substantial relationship between how far out we accommodate and how large we perceive objects to be. These phenomena sometimes exceed "optical" requirements for focused imagery at the retina and follow a pattern that might be linked to processing capacity. ***Second***, certain stimulus conditions systematically affect, but do not dictate, precise accommodative responses. Among such conditions must be included the dioptric parameters of lenses and lens-mediated imagery. ***Third***, there exist linkages between pupil dilation, ocular convergence, and accommodation that are generally complementary and mutually influential, but frequently decoupled. The synkineses among them apparently change consistent with their respective gain, plasticity, and stability characteristics. ***Fourth***, accommodation is affected by autonomic system states via both sympathetic and parasympathetic homeostatic and reactive innervations. ***Fifth***, while what is "attended" centrally must be considered important to accommodative response, peripheral stimulation also influences overall stimulus "adequacy." ***Sixth***, whatever theoretical framework is used to explain the relevant perceptual phenomena mediated by accommodation, it must deal with the physiological, optical, and perceptual effects of aging. The findings related to retinal stretch and ciliary muscle power suggest the accommodative system as a perceptual mediator, resistant to the impacts of age. The evidence seems to indicate that the flexible optical mechanics are likely to be very important, leveraged over an ever-diminishing effective optical range, but underpinned by more robust ciliary muscular dynamics.

The moon illusion seems to support an argument that how far away we sense an object to be but about which we may not be readily able to report a percept of distance, affects our perception of its size, which seems to be much more consciously "available". An efferent accommodative theory of size perception would readily explain the high correlations found by Nebbians between measured accommodation by highly labile eyes and judgments of size relative to a common standard.

As a strategy for the development of a predictive model of visual size and distance perception, a two-tier approach is proposed. The first treats active accommodation as a process. It involves accepting that there are a variety of internal and external stimulus conditions that influence the current state of accommodation, pupil dilation and ocular vergence, most critically for near distance responses. The second treats accommodation and its proximate efferents as state variables. These feed back critical scalar parameters, at the short end of an Archimedian lever, to higher pathways for the formation of conscious size and distance perception.

A **Tri-Centroid (T-O-P) Model**, illustrated in Figure 14, is the central component of an integrated perceptual-behavioral conceptual framework. The model defines the process and predicts the event-based state of accommodation as an accessible intervening response, predictive of perception. The first, lowest-order, process component proposed in this formulation is a **Tonic and autonomic-reactive** centroid, ***T***. The second, next higher, threshold-based process component is an **Optical and focal-demand** centroid, ***O***. The third, final, and highest order centroid is a **Processing capacity and information-demand** centroid, ***P***.

An essential characteristic of this general framework is a parallel processing assumption with both top-down and bottom-up components. Consistent with findings from physiological and comparative studies, redundant, distributed, and specialized processing of topographically registered "segments" of the visual array is carried out. This processing is dependent upon autonomic states and high-order criticality. It is carried out within the limits of available overall processing capacity and multiplexed channel bandwidth. Volitional, attentional, and experience-based parameters are assumed to be introduced via the highest order, ***P***, centroid at its broad and interactive boundary with cognition. Emotional, hormonal, and psychochemical inputs would be most directly mediated through the ***T*** centroidal component. Traditional psychophysical, threshold-bounded stimulus and sensory relationships, centered in retinal image quality, would define the ***O*** component vector.

An ***O*** component-dominant response would dictate efferents to accommodation toward the best-possible image quality at the retina independent of energy expenditure or information requirements. This represents the traditional ophthalmological assumption regarding the "attended" object, that we consistently and accurately accommodate to the object of interest and that optical image clarity conveys maximum information with no impact of ***T*** and a nulled filtration by ***P***. The ***O*** component operates in the present, with no historical influences. A variation of this, assuredly erroneous, position, has dominated display content and structural design engineering. The subsequent heuristic "tweaking" and formative engineering adjustments have always been expensive and are rarely followed by the kind of transfer of training research that might uncover significant perceptual misregistrations.

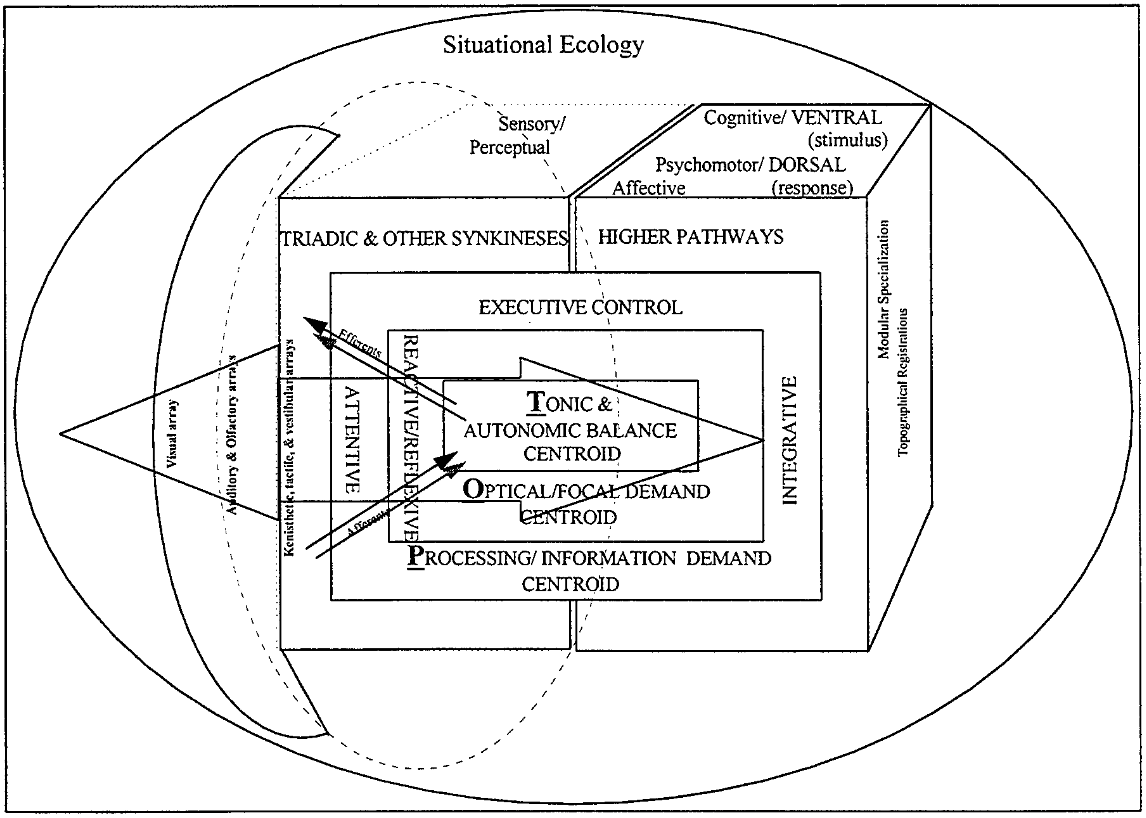


Figure 14. Tri-Centroid, *T-O-P*, Model as the core of a perceptual-behavioral conceptual framework. Tonic autonomic states establish baselines for individual behavior, modified, iteratively, by attentive executive control activity, short-loop reactive processes, and high level proactive informational demands and responsive behavior.

A ***T***-component-dominant response would result in a low energy tonic response, biased by current level of stress and resulting biochemical balance, independent of image quality or information requirements. This represents the extreme implication of the discovery of a resting state of accommodation and the ultimate state given an inadequate stimulus to accommodation or compensation by ***P*** for all deficiencies in ***O***. The ***T***-component is affected by past and anticipated states, but exclusively reactive to these.

A ***P***-component-dominant response would result in a degree of image clarity and size that provides the level of information demanded, maintaining an outcome-based relationship to energy expenditure and optical image quality. This represents a critical, high-level integrative intervention that, in effect, filters all imagery on the basis of adequacy, optimizing energy expenditure both at the level of retinal projection mechanisms and higher-order processing commitments. The ***P***-component is both reactive and proactive, both influenced by and influencing future states. A reduced model might characterize ***P*** as *the* critical component, relegating ***T*** to a "variable state" point of departure for all accommodation and ***O*** to a lawful set of relationships between photonic energy and its orderly translation to states dictated by ***P***.

To simplify, adequate stimulus and motivational states result in an expenditure of energy beyond tonic levels to change accommodation and its oculomotor partners to optimum states. These states may approach, or even exceed optical clarity requirements to define the ratio of total processing capacity per unit information in the image demanded to support perception. This fundamentally *oculomotor* model assumes the interaction of the three primary oculomotor synkinetic components, and the need to account for factors in the visual array known to affect each. Both *Where in the world?* and *What in the world are we looking at?* are relevant questions in this formulation. Even the more challenging and intimidating, *Why?*, bears critical weight. Measured accommodation is seen as both response to external stimulus conditions and a stimulus to internal processes and states, all of which affect perception.

CONCLUSIONS

The conceptual, logical conclusions and general direction of this background research effort are readily apparent. It is abundantly clear that visual accommodation may be affected by a wide variety of variables; this review has highlighted exemplars. In turn, accommodative states have been implicated as having intervening influence on perception.

What has not been discussed or examined in detail is the wealth of research and theoretical work on "Early Vision" or the higher precognitive processes that carry on the complex work of mature perception and attention. Modern theoretical and research efforts in stereopsis, texture processing, and the emerging complexities of depth and motion processing represent fields of study that, eventually as demonstrably as psycho-anatomy, should be completely complementary to the domains discussed here. That work, however, while decidedly beyond the scope and focus of this effort, should not be considered less important for that demarcation.

The next phase of this effort will introduce and conduct an experiment. This experiment will begin the work of addressing a variety of methodological and theoretical issues in the context of evaluating the relative impacts of previously manipulated variables on accommodation and, in turn, the perception of size and distance.

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APPENDIX A

Cognitive Style and other Higher Order Linkages to Accommodation

Pursuing briefly a line of thought introduced independently by both Wheatstone (1852) and Helmholtz (1867/1962) and apparent in discussions above, it seems that both physiological and psychophysical evidence support the participation of higher order cognitive and precognitive processes in the domain of perception.

In 1981 Imhoff and Levine concluded an extensive review of the literature on pilot selection and training, perceptual-motor, and cognitive research. Their objectives, in a contract effort for the then Air Force Human Resources Laboratory, were to identify those processes and abilities of demonstrated importance to successful piloting behavior and to identify and recommend a set of tasks/tests that tapped these processes and abilities. Their eclectic approach suggested a conceptual framework based on an information processing model and the need to recognize certain predispositional, experience-based and personality characteristics in a generalized model of aircrew behavior.

This conceptual framework supported the development of an operationally deployed, computer-based testing battery for aircrew selection and classification, implemented as the Basic Attributes Testing System, BATS (Acosta, 1985). The fielded battery included not only cognitive processing and psychomotor tests, but also several tests that accounted for unique and predictive variance from predispositional/ personality and cognitive style domains.

The eclectic conceptual framework compiled for the BATS, while productive in an applied setting, was similar in all fundamental respects to the much more elaborate and potentially powerful Activity theory, as discussed by Kaptelinin (1994). Both ecology and a variety of predispositional factors are equally valenced with biophysical processes, mechanisms, and structures in attempting to explain behavior and its specialized subset, performance.

The results of several of the cited size-distance perceptual studies, while primarily aligned in a traditional psychophysical measurement subdiscipline, suggest that both instructional sets and transformations in space and time between stimulus presentation and response parameters influence the measured outcome. Little in the literature reflects investigations into the impact of measurable predispositions or cognitive styles on "perceptual outcomes."

Two such tests, used with success in both automated and pencil-and-paper-based selection and classification batteries, are the Embedded Figures and the Mental Rotation tests. Embedded Figures is an emergent variation of the rod and frame paradigm, intended to reflect polar characteristics as either field-dependent or field-independent. One might anticipate that "field-dependent" styles would be much more influenced by foreground and background manipulations and the context in the stimulus array. Barber (1989) found an advantage for field-independent subjects in detecting, tracking and identifying smaller, higher speed targets in a complex scene. Focal demand manipulations associated with the target of interest should affect field-independent responders more effectively than the more scene-influenced field-dependent observers.

The Mental Rotation test reflects a component of imagery involved in the accurate transformation of a stimulus as it is transitioned in time and space. Logically, one might predict that more effective mental-rotators would reflect their facility at mental imagery transformation in a greater consistency and stability in and between size and distance judgments. This factor, measured in relation to the more traditionally psychophysical manipulations, may expand our understanding and, more explicitly, our question set regarding pre-cognitive, post-retinal influences on mature perceptual phenomena.